US Army Corps
of Engineers
Waterways Experiment
Station

Technical Report REMR-CS-40
April 1993

2

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Impacts as a Source of Acoustic Pulse-Echo Energy for Nondestructive Testing of Concrete Structures

by A. Michel Alexander
Structures Laboratory

Prepared for Headquarters, U.S. Army Corps of Engineers

The following two letters used as part of the number designating technical reports of research published under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program identify the problem area under which the report was prepared:

	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

PRINTED ON RECYCLED PAPER

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Technical Report REMR-CS-40
April 1993

Impacts as a Source of Acoustic Pulse-Echo Energy for Nondestructive Testing of Concrete Structures

by A. Michel Alexander
Structures Laboratory

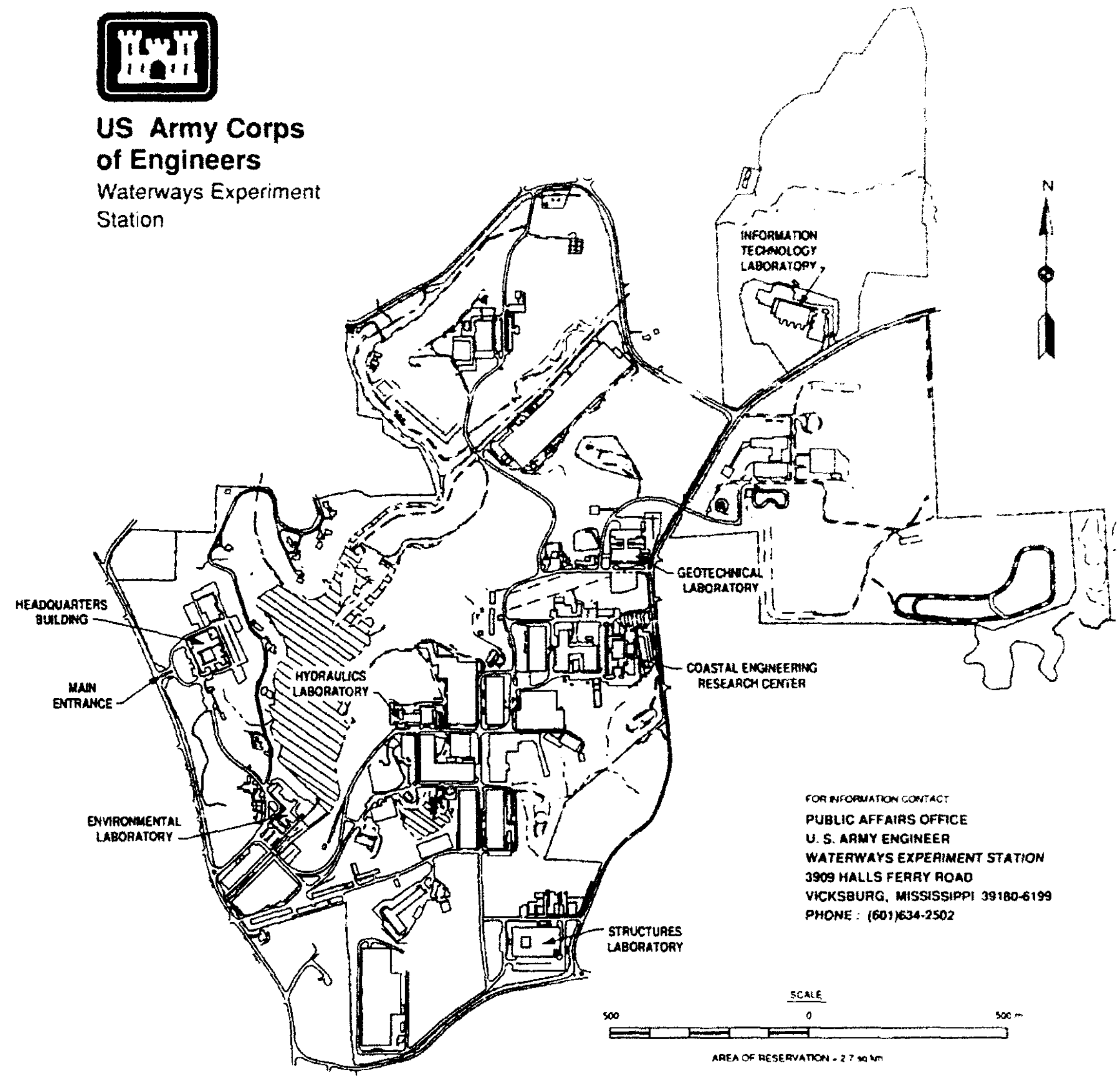
U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

US Army Corps
of Engineers
Waterways Experiment
Station



Waterways Experiment Station Cataloging-in-Publication Data

Alexander, A. Michel.
Impacts as a source of acoustic pulse-echo energy for nondestructive testing of concrete structures / by A. Michel Alexander ; prepared for U.S. Army Corps of Engineers.
84 p. : ill. ; 28 cm. — (Technical report ; REMR-CS-40)
Includes bibliographical references.
1. Concrete construction — Testing. 2. Nondestructive testing. 3. Ultrasonic testing. I. United States. Army. Corps of Engineers. II. U.S. Army Engineer Waterways Experiment Station. III. Repair, Evaluation, Maintenance, and Rehabilitation Research Program. IV. Title. V. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; REMR-CS-40.
TA7 W34 no.REMR-CS-40

PREFACE

The research reported herein was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Concrete and Steel Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Work Unit 32638. Mr. William F. McCleese, US Army Engineer Waterways Experiment Station (WES), was the REMR Program Manager. Dr. Tony C. Liu, HQUSACE, was the Technical Monitor. Mr. William N. Rushing was the Coordinator at the Directorate of Research and Development, HQUSACE. Mr. James E. Crews, HQUSACE, and Dr. Liu served as the Overview Committee.

Mr. James E. McDonald, Concrete Technology Division (CTD), Structures Laboratory (SL), WES, was Problem Area Leader. Mr. A. Michel Alexander, CTD, was the Principal Investigator of Work Unit 32638 during the research. Mr. Alexander performed the research and wrote the report. Appreciation is extended to Mr. Charles R. Welch, Explosion Effects Division, SL, for his help in the underwater explosives investigation.

The study was conducted under the general supervision of Mr. Bryant Mather, Director, SL; Mr. James T. Ballard, Assistant Director, SL; Mr. Kenneth L. Saucier, Chief, CTD; and Mr. Steven A. Ragan, Chief, Engineering Mechanics Branch, CTD.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

A - area of crystal, square metres
a_l - angle of incident longitudinal wave
a_s - angle of reflected shear wave
C - static capacitance of transducer, farads
F - frequency of pure tone, hertz
f - frequency of resonance in concrete, hertz
f_r - resonant frequency of transducer, hertz
f_1 - frequency of response at -3 db down on one side of peak, hertz
f_2 - frequency of response at -3 db down on other side of peak, hertz
$F_r(f)$ - frequency response of filter
$S(f)_i$ - input signal in frequency domain
$S(f)_o$ - output signal in frequency domain
$I(t)$ - impulse response of filter
K_3 - dielectric constant of piezoelectric crystal
L - inductance of external transducer inductor, henries
l - thickness of concrete slab, feet
Q - Quality factor of transducer
R - internal resistance of transducer, ohms
$R1$, $R2$, $R3$ - resistances of admittometer, ohms
T - period of wave, microseconds
th - thickness of crystal, metres
V - velocity of longitudinal velocity in concrete, feet/second
$V(t)_i$ - input signal in time domain
$V(t)_o$ - output signal in time domain
β_s - angle of refracted shear wave
β_l - angle of refracted longitudinal wave
ϵ_o - permittivity of free space, 6.85×10^{-12} farads/metre
λ - wavelength of stress wave, feet
ν_l - velocity of longitudinal wave, feet/second
ν_s - velocity of shear wave, feet/second
τ - width of rectangular pulse, microseconds

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
inches	25.4	millimetres
pounds (force)	4.448222	newtons

IMPACTS AS A SOURCE OF ACOUSTIC PULSE-ECHO ENERGY FOR NONDESTRUCTIVE TESTING OF CONCRETE STRUCTURES

PART I: INTRODUCTION

Background

1. The construction industry lags behind some of the other industries in the development of nondestructive testing (NDT) systems for one of its primary materials, concrete. No ultrasonic pulse-echo (UPE) system exists that will permit measurements to be made deep within a structure. Stress waves techniques are needed to probe the hidden features of concrete structures to make their interior characteristics and condition visible.

2. Traditionally, to determine the integrity of concrete structures nondestructively by stress waves, diagnosticians have listened to the auditory response of the concrete both to an impact with a hammer and by dragging a log chain across the structure. A clear ringing sound is heard when a chain is dragged or a steel rod or hammer is tapped over nondelaminated concrete (American Society for Testing and Materials (ASTM) 1992). This is the method of ASTM D 4580 as illustrated in Figure 1. A dull or hollow sound occurs when dragging or tapping on delaminated concrete. Impacts might have greater potential for flaw detection and deterioration measurements in concrete if the energy level and frequency content of the complicated waveforms generated by these impacts and reflected from the concrete interfaces could be classified in clear scientific terminology. If the auditory response could be replaced with a transducer and electronic display, they would better perform the "listening" and would provide quantitative data for analysis.

Shortcomings of Piezoelectrics

3. For reasons of repeatability and the advantages of electronic operation, it is desirable to use piezoelectric materials to generate and detect the stress wave energy needed to interrogate the quality of materials.

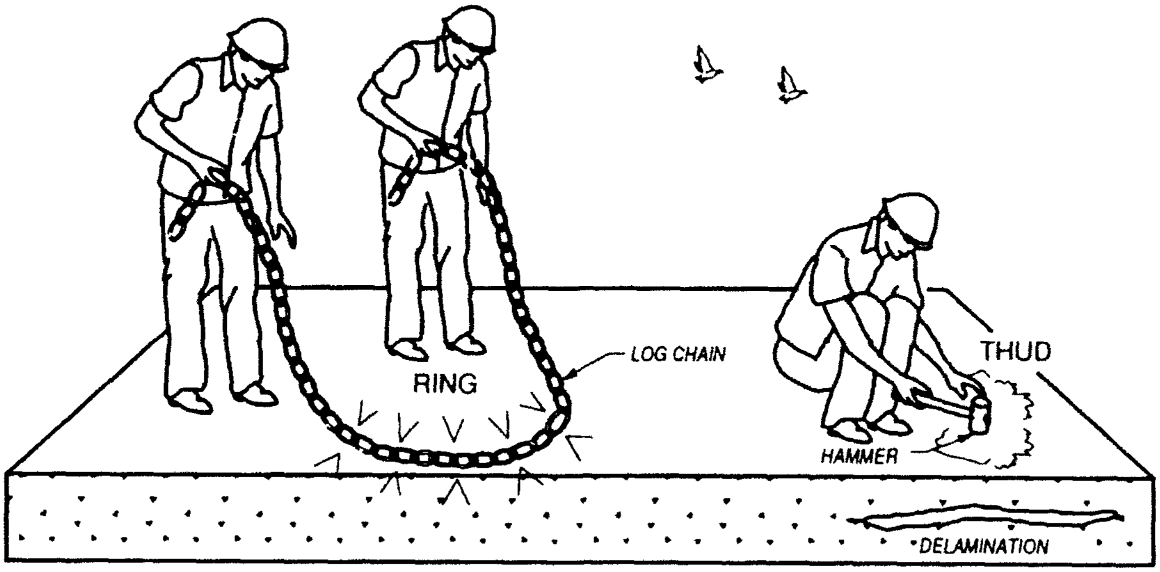


Figure 1. Quality of concrete tested by auditory response to impact

However, piezoelectrics have shortcomings at the frequencies necessary for operation in concrete. Due to the large grain size from coarse aggregates in the concrete, concrete flaw detection measurements require operation at a frequency of 200 kHz or less (Jones 1953). Otherwise, the concrete will not appear homogeneous to the stress wave, and excessive scattering will result, Figure 2. (This obviously places a lower limit on the size of the defect that can be detected.) The problem is that 200 kHz is on the low-frequency side of efficient piezoelectric operation. The stress level generated from a piezoelectric element is directly proportional to the square of the frequency; therefore, piezoelectric materials do not perform well in the kiloHertz range required for proper operation in concrete. Impacts generate high energy at low frequencies and, therefore, appear especially useful as a source of low-frequency energy for pulse-echo measurements in concrete.

4. Piezoelectric transmitters that operate at low frequencies have an excessive ring-time and, hence, pulse length for proper operation in concrete. Jones (1962) reports that due to the difficulty of damping low-frequency piezoelectric transducers (100 kHz), it is impossible to operate a common transmitter-receiver system to perform ultrasonic pulse-echo measurements in concrete as is so common with high-frequency pulse-echo measurements on metals. Even if the transmitter ringdown could be reduced to as low as five

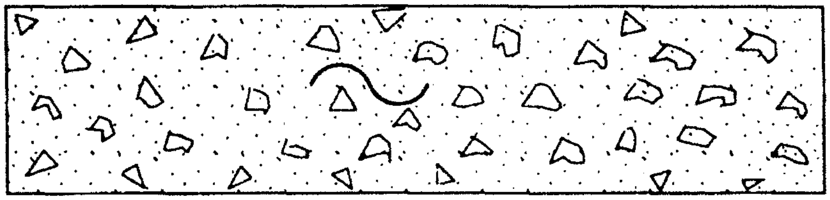


Figure 2. Wavelength must be equal to or larger than dimensions of coarse aggregate for material to appear homogeneous to stress wave

cycles, the pulse length in the concrete would be about 7 in.* for a transducer operating at a resonant frequency of 100 kHz. Since five cycles is equivalent to five wavelengths in the concrete, then

$$\lambda = \frac{v}{f} \tag{1}$$

$$\lambda = \frac{15{,}000}{100{,}000} \tag{2}$$

$$\lambda = 0.15\ ft \tag{3}$$

where

λ = wavelength, feet

v = ultrasonic pulse velocity in concrete, feet/second

f = transducer frequency, hertz

the pulse length would be 0.75 ft (5λ). This means that the resolution obtained from a thickness measurement on concrete pavement or floor slab (less than 10 in. thick) would be poor. The resolution would be even worse for detecting discontinuities a few inches from the top surface than it would be for detecting the back surface (thickness measurement). As a minimum, the pulse length should be no longer than 10 percent of the travel path (the travel path is twice the thickness) to obtain proper resolution. The pulse length at 100 kHz for a ring-time of five cycles is simply too large a percentage of the total travel path for the low frequencies that concrete

---

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 9.

requires for proper resolution. With impacts, however, this pulse length can be controlled.

5. Although the author developed an ultrasonic pitch-catch system using piezoelectrics that had a short ring-time of about three cycles, the output of the piezoelectrics did not enable a penetration depth greater than 1 ft (Thornton and Alexander 1987). A thickness measurement through 9 in. of concrete is illustrated in Figure 3. Because of the difficulty in developing a damped piezoelectric transmitter having a short pulse length and in addition maintaining sufficient power output to penetrate the concrete, it seems promising to introduce the energy into the concrete by impact with a hammer. Previous tests with impact measurements on concrete piles (Alexander 1980) revealed the presence of high-level sonic energy and also lower-level ultrasonic energy. Because an impact does not ring (shape of pulse resembles a half sine wave rather than a damped sinusoid from a piezoelectric) and the pulse length and intensity can be controlled by the characteristics of the hammer, the hammer offers a suitable choice for use as a source of stress wave energy for use on concrete.

Advantages of Impacts

6. Other advantages of impacts are the quickness, convenience, and simplicity of the measurement operation. A small contact area on the concrete surface from a hammer impact makes it unnecessary to grind the surface for smoothness and flatness. Physical experience teaches us that hammers are unmatched when it comes to introducing significant amounts of energy into a concrete structure to break up its composition. Concrete is highly resistant to destruction, but one can do that very thing with a jackhammer. If one desires to drill a hole in concrete, he can best do it with an impact drill. Hammers can develop such sharp and intense impacts that the energy produced in a very short time frame is considerable. Also by varying the dimensions, hardness, and mass of the hammer head, the frequency content of the stress pulse can be chosen. It is a proven and common technique to use impacts, usually explosives, to make seismic refraction explorations in the earth for engineering site investigations (Redpath 1973). Figure 4 illustrates an example of the high energy available from impacts at low frequencies.

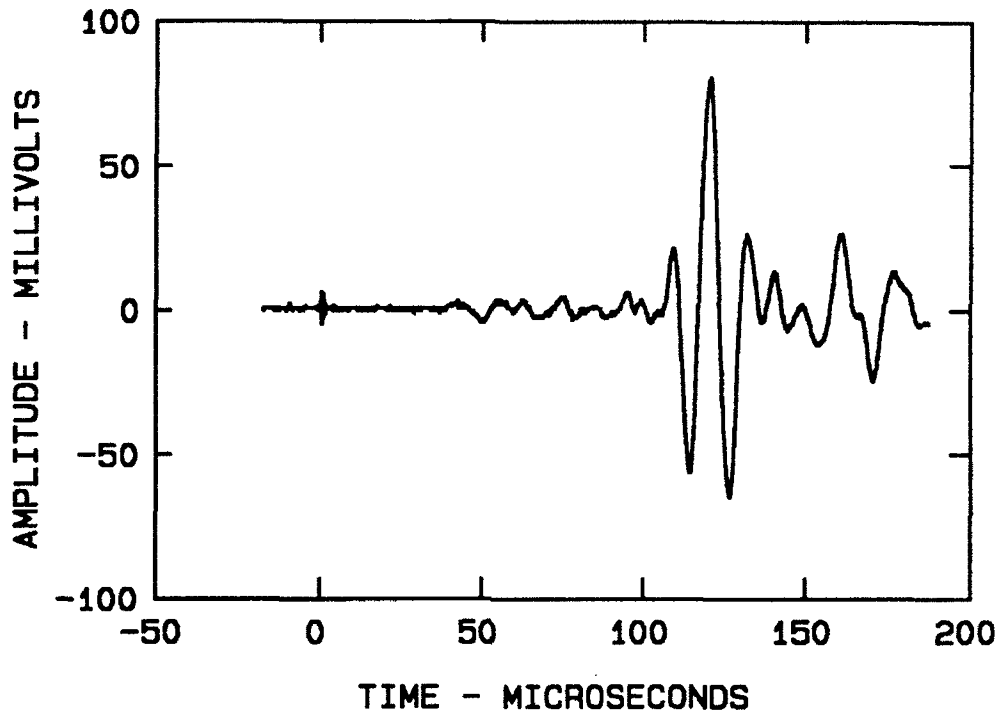


Figure 3. Lead-metaniobate wideband transducer with reduced ring-time of about three cycles at center frequency of 200 kHz. The large amplitude pulse arriving at 100 μsec is an echo from the back surface of a 9-in.-thick concrete slab

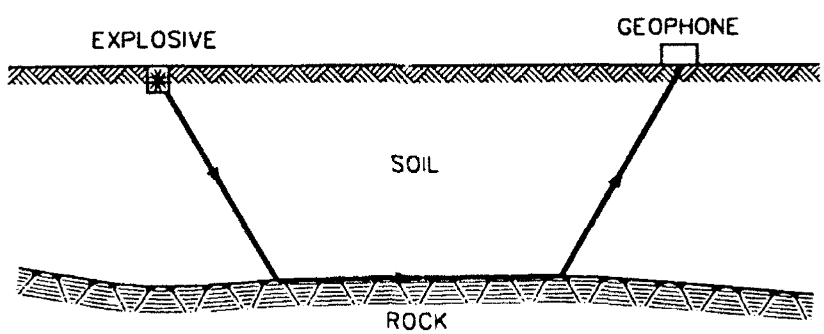


Figure 4. The use of impacts to generate high levels of stress wave energy is important for geotechnical applications. The seismic refraction technique is used for engineering site evaluations and oil exploration

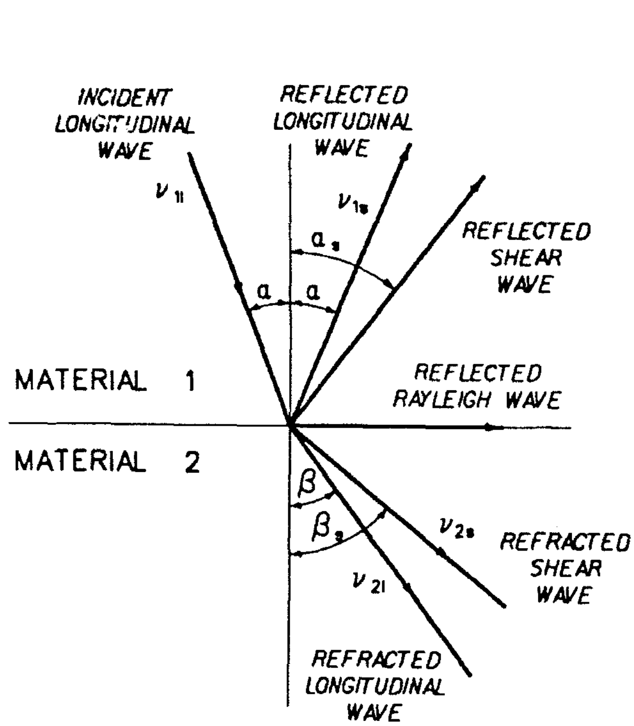
Disadvantages of Impacts

7. The use of impacts makes it necessary that electrical filtering be used. Since the radiation of the energy from an impact consists of (a) a beam of energy having a wide angle of divergence with little directionality and (b) a wide band of frequencies, numerous modes of vibration are excited in the concrete structure and in the crystal detector. Because all modes other than the desired longitudinal mode in the concrete are noise for all practical purposes, electrical filtering and other signal processing techniques will be required to eliminate or attenuate the extraneous energy. Figure 5 illustrates the generation of undesired modes as well as the desired refracted and reflected longitudinal wave when the rays of ultrasonic energy are not normal to the surface of the concrete.

8. The pattern of energy emanating from the impact area has a wide angle of divergence, and, as a result, the beam pattern lacks directivity. This indicates that (a) the energy density that irradiates a reflecting interface is small and will return a weak echo and (b) the detected echoes may not come directly from below the receiver transducer as would be desirable to accurately locate the source of the interface or discontinuity. Figures 6 and 7 illustrate the sound profile of a point source and a plane source.

9. One cannot continuously display impact signals on nonstorage analog oscilloscopes since they are one-shot rather than repetitive events. Also, the hammer cannot be swung at a rapid enough and uniform rate to maintain a continuous display on the oscilloscope screen as can be done with piezoelectric transducers. By using a digital oscilloscope or similar recording device having storage capability, rather than the traditional analog oscilloscope which does not, the necessity of requiring a series of impacts to maintain a visible trace on the oscilloscope screen can be eliminated. One impact is sufficient to capture the data. However, it may be useful to average a number of measurements from a series of impacts in order to eliminate random noise.

10. The level of stress generated from a hammer is not repeatable from one impact to the next. However, a changing stress amplitude (within certain bounds) is not an important consideration because pulse-echo measurements are



SNELL'S LAW:

$$\frac{\sin \alpha}{\nu_{1l}} = \frac{\sin \beta}{\nu_{2l}} = \frac{\sin \alpha_s}{\nu_{1s}} = \frac{\sin \beta_s}{\nu_{2s}}$$

Figure 5. Problem of mode conversion and presence of spurious waves when incident longitudinal wave is not normal to target surface

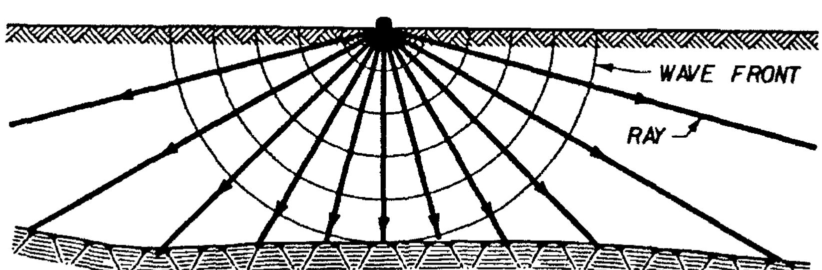


Figure 6. A small-diameter source relative to the wavelength generates a spherical wave with considerable mode conversion which complicates an ultrasonic pulse-echo measurement

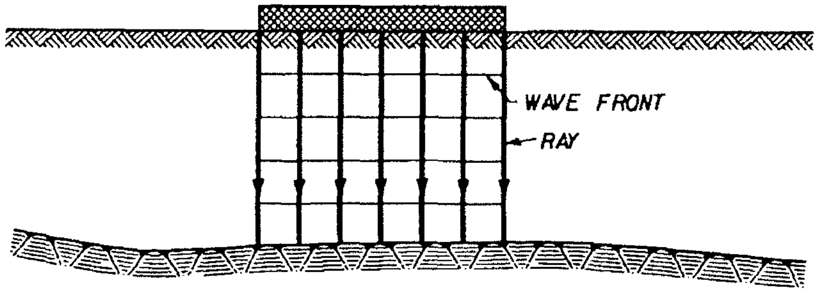


Figure 7. A large-diameter source generates a plane wave without mode conversion and simplifies ultrasonic pulse-echo measurements

primarily based on the measurement of time-of-arrival (TOA) and the time-separation of echo signals.

PART II: THEORETICAL CONSIDERATIONS

General Signal Characteristics

11. One important aspect in understanding ultrasonic pulse-echo measurements using impacts is a knowledge of the frequency characteristics of various continuous waves and transient signals. Any signal can be represented by the sum of individual sine waves having various frequencies, amplitudes, and phases. A pure tone is a sinusoidal wave of infinite duration, and its representation in the frequency domain is a single spectral line at the frequency, $F = 1/T$, where T is the period of the sinusoidal wave. In Figure 8, a complex harmonic tone is made up of the sum of the fundamental frequency and the second harmonic. This is a signal of infinite duration (continuous wave) although represented in an abbreviated form.

12. There are two important ways to view or picture information in a signal as shown in Figure 9: the time domain and the frequency domain. A general principle observed is that signals which are broad in one domain are narrow in the other domain. The sinusoidal signals are continuous (broad) in the time domain, but the resulting frequency spectrum has discrete (narrow) lines at the frequency where the energy exists. Figures 9b and 9c illustrate the two views of a signal: a signal in the time domain consisting of the sum of a fundamental frequency and the second harmonic and two narrow spectral lines in the frequency domain representing the two sine wave components making up the complex harmonic tone in the time domain.

13. Figure 10 shows (a) one sine wave of continuous duration, (b) one square wave signal of continuous duration, and (c and d) two transient signals, a damped and a highly damped sinusoid, of finite duration (Hewlett-Packard 1981). As mentioned, the sine wave and square wave of continuous duration have spectra of energy that exist at discrete frequencies which are represented by narrow vertical lines of various amplitude. The energy of a continuous sine wave exists only at one discrete frequency. The energy of a continuous square wave exists only at the discrete harmonic frequencies. However, the opposite of that is true with the next two signals having short duration in the time domain. Each of these signals develops spectra that are

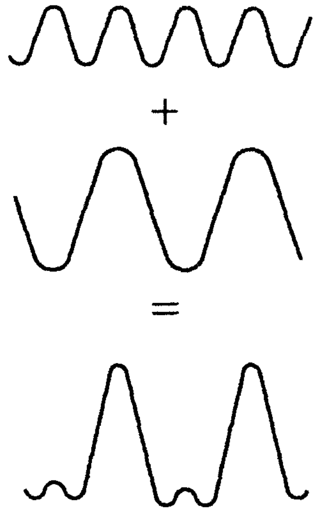


Figure 8. Any real waveform can be produced by the correct combination of sine waves (Hewlett-Packard 1981)

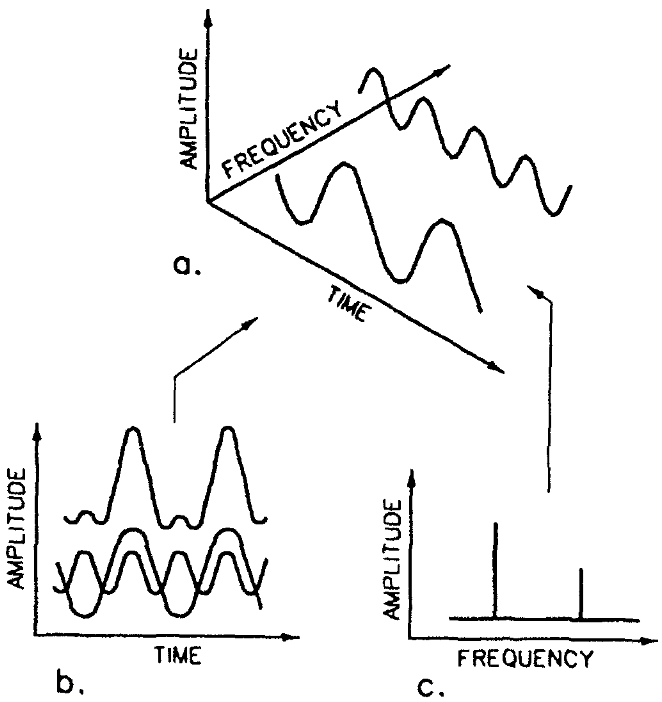


Figure 9. The relationship between the time and frequency domains: (a) three-dimensional coordinates showing time, frequency, and amplitude, (b) time-domain view, and (c) frequency-domain view (Hewlett-Packard 1981)

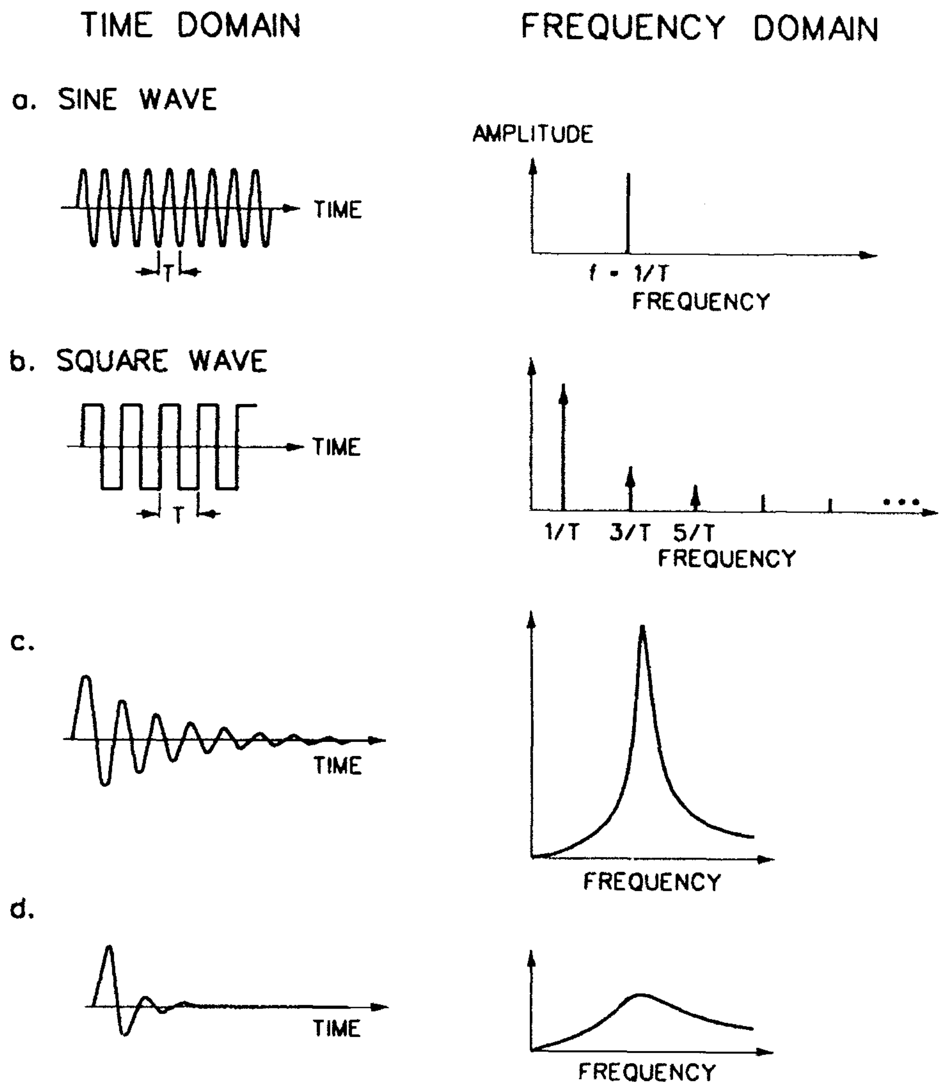


Figure 10. Types of long- and short-duration signals with corresponding frequency spectra. When time signals are wide and continuous, (a) and (b), the frequency spectra yield discrete and narrow bands of energy; and when the time signal is narrow, (c) and (d), the frequency domain yields wide continuous bands of energy (Hewlett-Packard 1981)

of continuous-band character. It is the latter signals that concern UPE measurements in concrete.

Impact Signal Characteristics

14. Impact devices that create short pulse widths having sharp rise times should introduce high enough frequencies into the concrete to make ultrasonic measurements. The typical shape of a load-pulse from a hammer impact is shown in Figure 11, and the corresponding frequency spectrum of the pulse is shown in Figure 12. The spectrum will dip to a minimum at points on the x-axis where the frequency difference between the points is equal to the reciprocal of the load-pulse duration. The first dip will occur at a frequency of 1.5 times the frequency difference. It will then produce a spectrum that resembles the locus of a bouncing ball, with dips occurring at integral multiples of the frequency difference. The maximum energy generated as a function of frequency for a given impact exists at zero hertz. Most of the energy exists at low frequencies that cause spurious modes of vibration (in the concrete and transducer receiver) that can interfere with the recognition of the desired ultrasonic echoes. It then is necessary to use an electrical filter to reject undesirable vibration noise. A sharp load-pulse can develop energy up to frequencies of a few megahertz, and even though the high-frequency attenuation property of concrete is high, there is enough energy reflected from the concrete interfaces at the lower frequencies to sufficiently excite resonances in a piezoceramic receiver up to a few 100 kHz. As illustrated in Figure 10, the shorter the time the pulse exists in the time domain, the broader the spectrum is in the frequency domain. Note that the reciprocal of the contact time determines the frequency difference between the points where the curve touches the x-axis.

Transducer Characteristics

Damping transducers

15. Although it is not very efficient to damp a piezoelectric element used as a transmitter, it is possible to damp an element used as a receiver without an excessive loss of sensitivity. Although damping the receiving

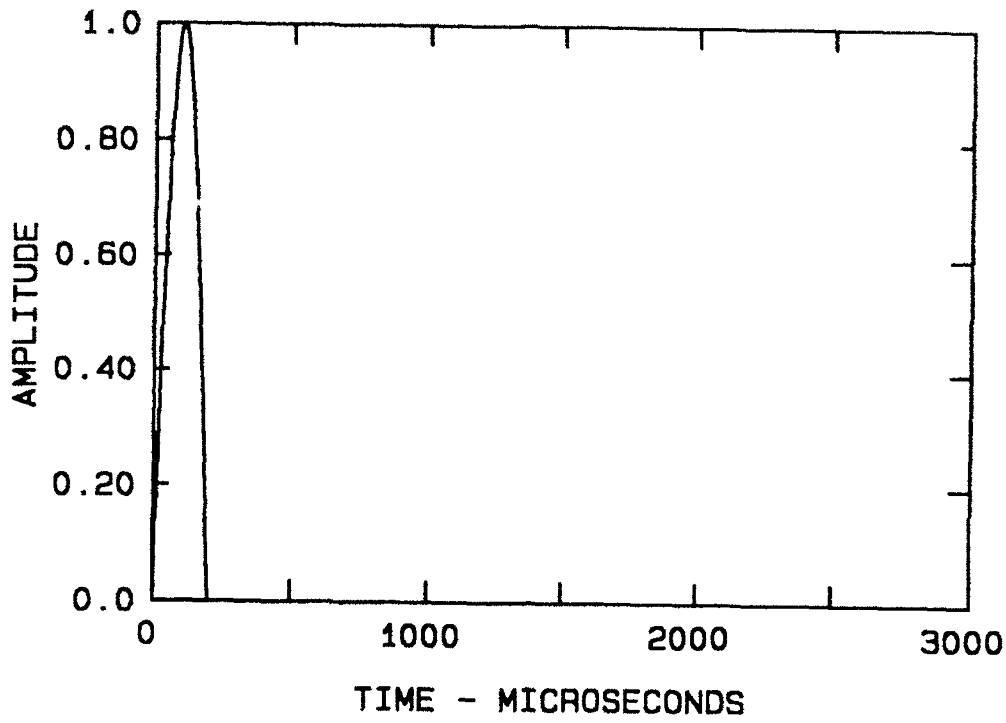


Figure 11. Typical shape of force-time load-pulse from impact of hammer on concrete surface. The shorter the pulse duration, the higher the resolution of the measurement

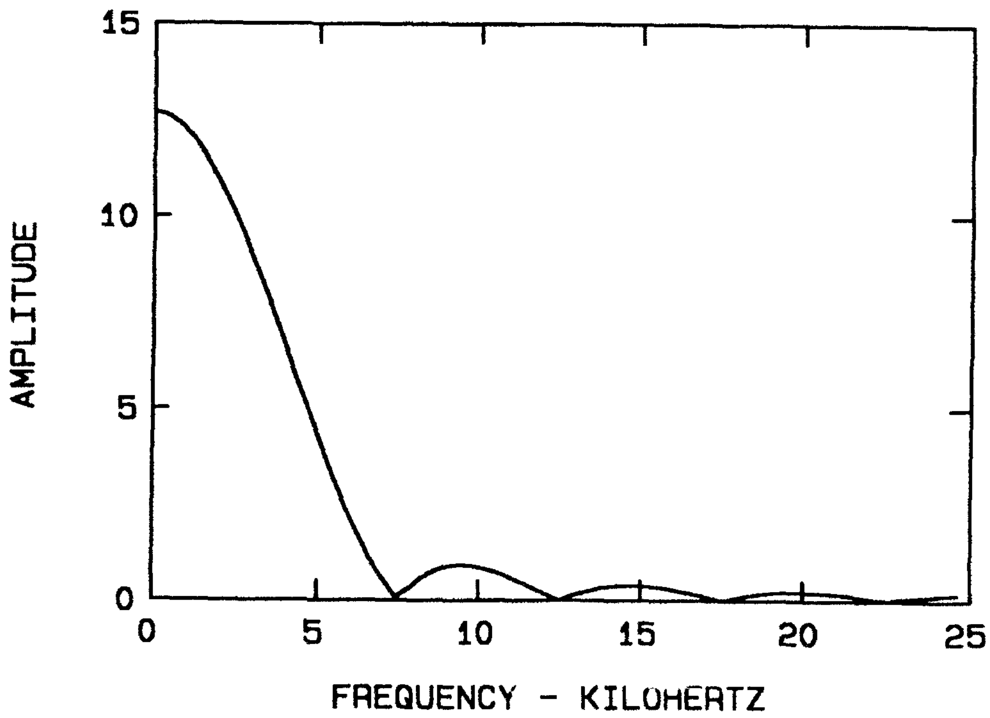


Figure 12. Frequency spectrum of previous time-domain signal showing distribution of energy with frequency. Difference between frequency at energy dips is equal to reciprocal of pulse duration

transducer lowers its sensitivity similar to the transmitter, it is not as critical as with the transmitter, because low-level signals from the receiver can be increased by electronic amplifiers. No similar amplification can be applied to the transmitter output to increase the mechanical energy to the concrete.

Damping techniques

16. A primary effort was made to determine the state of the art of damping piezoelectric materials for preventing excessive ringing (Thornton and Alexander 1987) in the transducers. Transducer companies were reluctant to discuss the type of materials and techniques that they use to obtain various bandwidths and sensitivities of piezoelectric elements since this is proprietary information. However, it was possible to find useful information in the literature. A number of investigators have performed research on the damping of piezoceramics with epoxy-loaded backings to obtain desired bandwidths (Kossoff 1966, Washington 1961, and Lutsch 1961). A mixture of epoxy and tungsten powder will produce a backing that has an approximate acoustic impedance match with that of PZT. (PZT is a tradename used by Vernitron Piezoelectric Division of Bedford, Ohio, to represent the type of piezoelectric material called lead zirconate titanate. Although many people still refer to all lead zirconate titanate piezoelectrics as PZT, other manufacturers have their own nomenclature.) This match will produce a minimum of reflection at the PZT/backing interface and allow most of the energy leaving the back face of the crystal to enter into the backing. Figure 13 illustrates the location of the backing used to damp a crystal (Carlin 1960). If the pulse reflects back into the crystal, it will cause ringing. Lutsch (1961) also used rubber powder in the backing to increase the attenuation and reduce reflections from the back end of the backing. Washington (1961) found that a mixture ratio of 2:1 by mass of tungsten to epoxy produced a satisfactory backing. Increasing the amount of tungsten above this produced marginal improvements. Kossoff (1966) found that a one-quarter wavelength layer matched to the load and a low-impedance backing that was also a one-quarter wavelength thick gave the best bandwidth, with reduced sensitivity. He worked with PZT-7A.

17. There are mainly three different ways to damp a transducer. First, a Hopkinson Bar, which has a long backing behind the transmitted pulse, can be

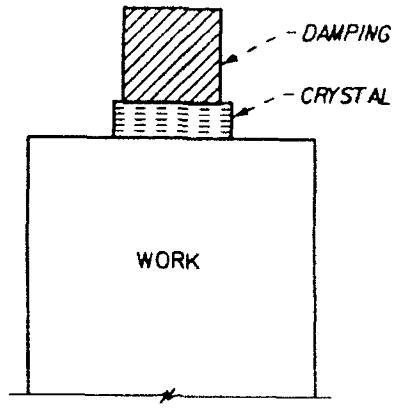


Figure 13. Illustration of how backing is applied to piezoelectric element for damping purposes to alter bandwidth (Carlin 1960)

used. This serves to delay the echo from the back end of the bar until echoes have been received by the transducer from the concrete. Second, a shorter backing can be used to damp the transducer. This backing matches the crystal in impedance but has high attenuation properties to dissipate the energy leaving the back face of the crystal to eliminate the development of standing waves in the backing. This same idea is used with electrical power transmission lines to prevent reflections. And finally, the third technique involves using a one-quarter wavelength backing that does not compromise the sensitivity of the transducer as much but gives a wider bandwidth. Canfield and Moore (1967) tried to use this technique in a transducer to measure the thickness of concrete but had limited success. The purpose then of matching impedances is to terminate the back face of a crystal in its characteristic impedance. By definition, the characteristic impedance of a material is the impedance required to eliminate reflections. As in electrical cables, an infinite length is not required for a backing in ultrasonics to eliminate standing waves.

Impulse response

18. A theoretical waveform that is used in physics and mathematics to describe many concepts (point mass, point charge, point sources, etc.) is the impulse (Figure 14). An impulse is a mathematical pulse having an infinitely

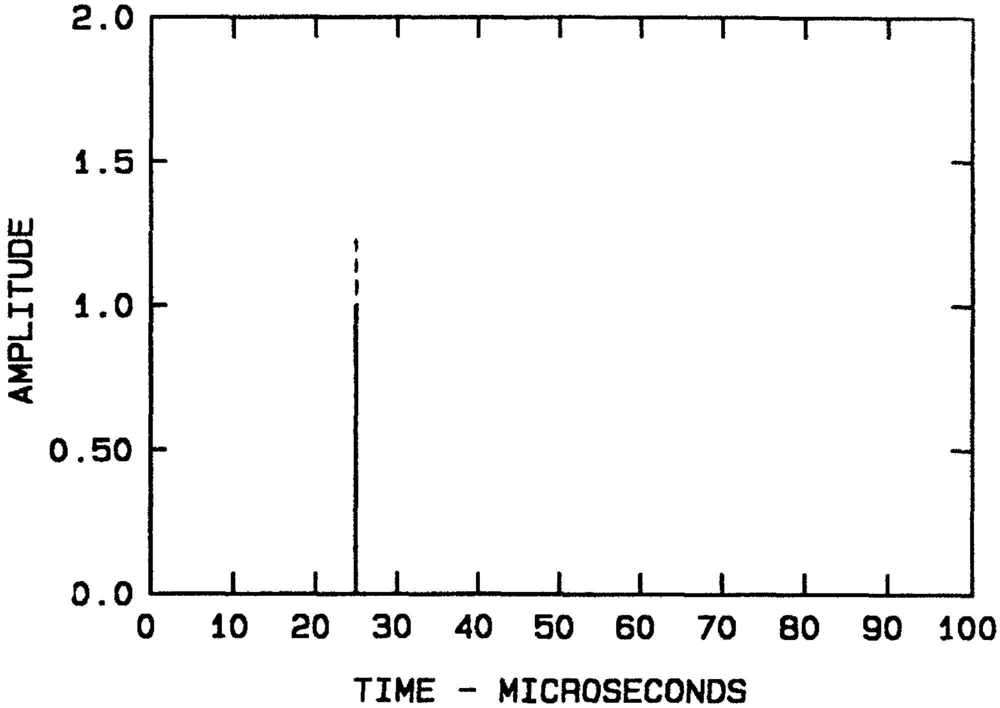


Figure 14. A mathematical impulse has an infinite amplitude at one instant in time. A real-world impulse will have a definite amplitude and will exist for a definite (although short) period of time

large amplitude and a width of zero units of time in duration. It therefore contains energy at all frequencies uniformly across the spectrum (Figure 15). The application of a mechanical impulse to a mechanical system produces an effect which defines the system in the limit. A system is totally described by the application of an impulse. If a transducer is excited by an impulse, it will exhibit all fundamental modes of vibration with all of the respective harmonics for that fundamental. None will be left out and the response will approach a definite limit dependent on the system characteristics of the transducer. This definite limit is called the impulse response of the transducer.

19. Imagine the process to be started by exciting the transducer with a fairly wide pulse and observing the response. As this process is continued by making the exciting pulse somewhat shorter each time, the response will finally settle down to a definite form. From that point on, the response will be final. Even though the applied pulse contains higher-frequency components

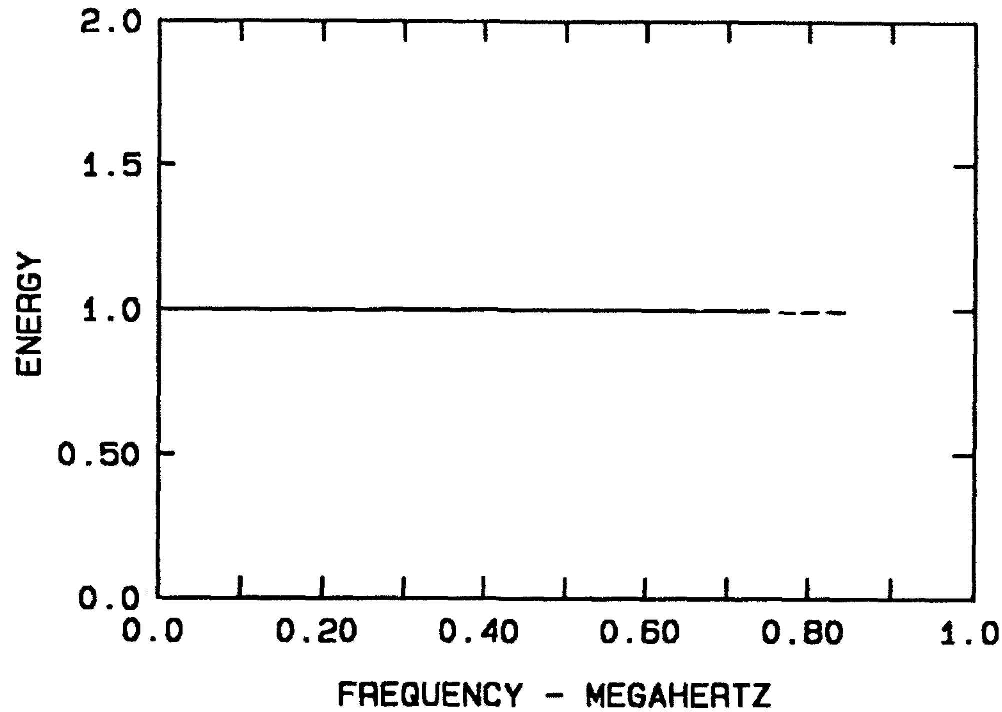


Figure 15. Energy is generated at all frequencies from an impulse. A real-world impulse will generate frequencies high enough to cover the range of the system tested

that distinguish the pulse as different from the previous pulse, it will produce a negligible change in the transducer response. Every transducer, instrument, material, or system has a limit in its frequency response. Once the applied pulse produces the final response, there is no need to make the applied pulse any shorter in time in an effort to improve the measurement. The time duration of the applied pulse should always be much smaller than the period of the greatest frequency of interest in the system being tested. In fact, even the shape of the applied pulse is not important once it has become short enough to generate the frequencies that the transducer will respond to. The pulse can be triangular, rectangular, or any shape. It is implied that the resolving power of the amplifier and recording equipment be sufficiently adequate to cover at least the range of frequencies that the transducer will respond to.

20. A fairly intense pulse can be generated by striking a common carpenter's hammer on the surface of concrete, but the duration of the pulse lacks the brevity needed for making UPE measurements with the proper

resolution. Fairly short pulses can be generated by dropping steel balls against the surface of concrete, but the applied pulse lacks the necessary intensity for measurements of deep penetration in the concrete. An impact is needed that will have both attributes for efficient pulse-echo measurements in concrete.

21. The textbooks that deal with the response of various systems (filters, transducers, etc.) use an idealized stimulus such as an impulse to describe the transient response (Pender and McIlwain 1950). Although the impulse (infinitesimal width and infinite amplitude) does not exist in the real world, it can be approximated close enough with a rectangular pulse. The pulse need only be short enough in duration to contain the frequency components that cover the bandwidth of the particular transducer. As the rectangular pulse becomes shorter and shorter, the response of the transducer finally reaches a limit so that the waveform changes no more. This final waveform is called the transient response.

Tuning of transducers

22. It is important that the electrical impedance of the transducer matches the electrical impedance of the receiving or transmitting circuitry. Electrical matching of impedances is important to obtain maximum efficiency from a transmitter or receiver (Walker and Lumb 1964). When the bandwidth of a receiving transducer has been increased [Quality Factor (Q) lowered] by an external backing member, the sensitivity will be reduced from that of an air-backed element. However, some of that sensitivity can be regained, without degrading the bandwidth, by tuning out the reactance of the static capacitance of the transducer by the addition of an inductor. Even if the piezoelectric transducer does not require heavy damping with a backing material, its output can still be boosted by the addition of an inductor. The frequency of electrical resonance created by the combination of the externally added inductor and the transducer capacitance is tuned to equal the mechanical resonance of the crystal.

23. The shunting effect of the static capacitance generally is undesirable, whether the device is designed for operation at resonance or for broadband (below resonance) operation. In electrically driven devices, it (static capacitance) shunts the driving amplifier or other signal source requiring that the source be capable of supplying extra current. In the case

of mechanically driven devices, such as is the case here, the static capacitance acts as a load on the active part of the transducer, reducing the electrical output. In nonresonant devices, little can be done about the shunt capacitance except choose a type of piezoelectric material that has maximum activity. In resonant devices, however, the static capacitance may be "neutralized" by employing a shunt or series inductor chosen to resonate with the static capacitance at the operating frequency. This is illustrated in Figure 16 (Vernitron Piezoelectric Division 1979).

24. The static capacitance (C) can be measured with an impedance bridge or calculated. If measured, it should be made at a low frequency near 1 kHz. If calculated, one can use the following equation (Edo Western Corporation Brochure)

$$C = \frac{K_3 \epsilon_0 A}{th} \tag{4}$$

where

K_3 = relative permittivity, dielectric constant of crystal

ϵ_o = permittivity of free space, 8.85×10^{-12} farads/metre

A = area of crystal, square metres

th = thickness of crystal, metres

C = static capacitance, farads

25. Impedance matching on a transducer is achieved with an external inductor, once the inductance value is determined from Equation 6. At the frequency of resonance, the inductive reactance is equal to the capacitive reactance of the series branch shown in the equivalent circuit of Figure 17 (Cady 1964). At that frequency, the total impedance of the series branch is purely resistive and equal to R. The inductive reactance cancels the capacitive reactance. Since C1 will reduce the output voltage coming from R (the generator), an inductor can be placed in parallel with C1 to form a high-impedance parallel resonant circuit. Of course, the resonant frequency of the parallel circuit is made equal to the resonant frequency of the series circuit by choosing an inductor that matches the value of the static capacitance. The familiar equation for the resonant condition is rearranged in the following steps to solve for the inductance

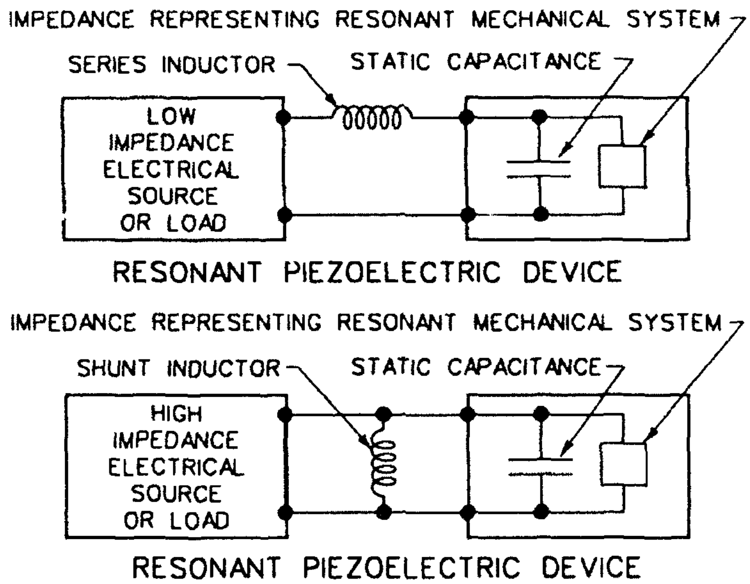


Figure 16. Resonant piezoelectric device with static capacitance "neutralized" by inductor (Vernitron Piezoelectric Division 1979)

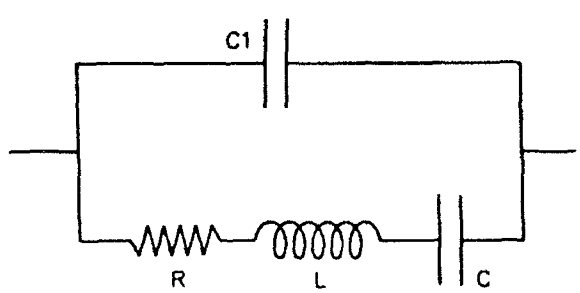


Figure 17. Equivalent electrical circuit of piezoelectric resonator (Cady 1964)

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{5}$$

$$L = \frac{1}{(2\pi f)^2\ C} \tag{6}$$

where

L = inductance of coil, henries

C = static capacitance, farads

f = resonant frequency of transducer, hertz

26. The addition of an inductor across the piezoelectric transducer tuned to the appropriate frequency of the thickness mode oscillations is also useful to avoid undue excitation of the lateral ringing of the transducer elements at a different frequency (Bradfield 1948). It is necessary for admittance (reciprocal of impedance) measurements to be made in the process of constructing a transducer. The admittance of the piezoelectric transducer will change from its undampened condition in air. As elements are bonded together into a mosaic in various series or parallel combinations, the admittance will change. Other factors that alter the admittance are: the addition of external damping, the installation of the piezoelectric elements into a housing, the associated electrical impedance placed on the transducer by the cable, various receiving circuitry, and the mechanical loading by the test specimen.

Bandwidth measurements

27. Evaluation of the characteristics of the piezoelectric resonator is dependent upon accurate measurements of the physical and dielectric properties and impedance of the element or resonator. While the measurements of capacitance and dissipation factor are relatively simple (requires a capacitance bridge), the evaluation of the critical frequencies must be carefully performed. The recommended test circuit for determining the critical frequencies and impedances of the piezoelectric resonator is shown in Figure 18. With this type of measurement, the following parameters can be measured: the resonant frequency of the transducer (frequency of series branch in Figure 17), antiresonant frequency of the transducer (frequency of both branches in parallel), output impedance of transducer (R), Q or

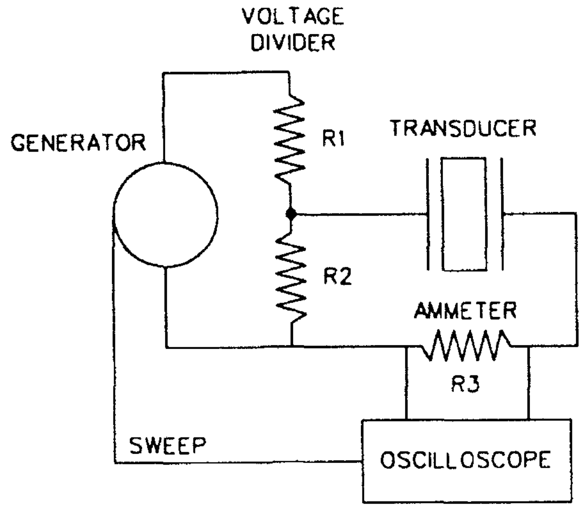


Figure 18. Admittometer used to measure bandwidth of piezoelectric transducers (Edo Western Corporation Brochure)

bandwidth, presence of interfering modes of vibration, and other useful information (Edo Western Corporation Brochure).

28. An automatic sweep oscillator was used in the admittance measurements. However, the measurements can be made by adjusting the frequency manually. The sweep oscillator used is capable of providing a direct-current sweep voltage for the horizontal axis of the oscilloscope that is directly proportional to the output frequency of the oscillator. By repeating the sweep at a suitable repetition rate, a continuous band-width curve is displayed on the oscilloscope as a function of frequency. The sweep rate must be lowered when the transducer has a high Q. A high Q transducer requires a definite amount of time for the amplitude to build up to maximum when excited near resonance. (Thornton and Alexander 1987) If the Q of the transducer is 10, it will take 10 cycles of sinusoidal excitation to build up to 96 percent of the full amplitude. A Q of 100 will require 100 cycles, etc.

29. Although the circuit seems relatively simple, there are some things to be aware of. The sum of R1 and R2 should match the output impedance of the sweep generator. The value of R2 should be kept much lower than the R of the transducer so that it will not introduce damping into the transducer circuit. Also, the low impedance will help maintain a fairly constant supply voltage

(necessary) across the resistor R2. Ideally, R3 should be kept low (less than R of transducer) for the voltage across R3 to represent accurately the admittance of the resonator. However, the voltage will drop so low across R3 at the antiresonant frequency that it will cause a poor signal-to-noise ratio. It is recommended that R3 be less than three times the value of R for proper signal-to-noise considerations. This will require that a correction be made to calculate the admittance and the mechanical Q at resonance. In addition, there can be significant problems with stray inductance and especially stray capacitance due to the low values that make up the equivalent circuit of the transducer. Leads should be kept very short and care taken to use the proper test fixture. A low capacitance probe can be used to take the voltage from R3 to the oscilloscope.

30. A bandwidth measurement was made on a PZT-C5500 piezoelectric rod element that was 1 in. in length and 1/2 in. in diameter (Figure 19). The frequency constant of the cylinder was 56 kHz-in. Hence, with a 1-in. length, the crystal has a longitudinal resonance of 56 kHz. The photograph shows that the undamped crystal has a sharp Q (narrow peak response). This means that the energy is contained within a narrow band of frequencies. The equation for computing the Q is

$$Q = \frac{f_r}{f_2 - f_1} \tag{7}$$

where

f_r = resonant frequency, hertz

f_2, f_1 = frequencies above and below resonance where the amplitude is down by a factor of $1/\sqrt{2}$ (-3 db), hertz

A rough calculation of Q from this measurement follows

$$Q = \frac{56,000}{2,000} \tag{8}$$

$$Q = 28 \tag{9}$$

If a measurement were made, the time required (Q/f) for the crystal to ring down to 4 percent of its original amplitude would be 500 μsec (28/56,000). Obviously, a transmitter or receiver with a 500-μsec ring-down time could not

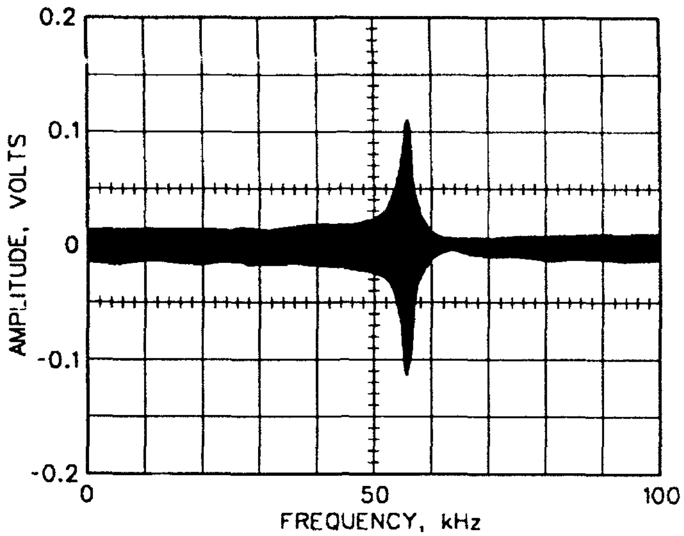


Figure 19. Bandwidth measurement on a PZT-C5500 piezoelectric rod element. Longitudinal resonance occurs at 56 kHz. The PZT rod element is 1 in. in length and 1/2 in. in diameter. PZT-C5500 is manufactured by Channel Industries

be used to detect an echo from the base of a 9-in. slab (102-μsec round trip) as it (transducer) would still be ringing at the TOA of the reflected signal. (The transducer would be initially excited into ringing at the instant of impact.) This example is presented as an illustration to point out the need for having a transducer receiver that is damped.

31. Notice how the bandwidth measurement, on a piezoelectric rod element, is clean and free of spurious nodes. The undesirable radial mode is above 100 kHz and falls outside the scale shown on the photograph. However, the large separation in frequency between the desirable longitudinal mode and the undesirable radial mode makes the transducer ideally suited for applying an electrical filter to remove the unwanted radial interference. A mosaic transducer could be constructed with a number of these point sources to form a flat radiator with directivity (Howkins 1968). The higher-frequency radial mode could be reduced, or eliminated, with low-pass filtering and by embedding the rod elements in a disc or plate made of tungsten-loaded epoxy. The frequency constant of PZT-C5500 is 56 kHz-in. in the longitudinal direction and 78 kHz-in. in the radial direction. This means that the interfering mode

would be three times as high in frequency as the desired mode for a 1-in.-long, 1/2-in.-diam rod element. Also, the concrete itself would act as a low-pass filter, since the attenuation property of concrete is very high when the wavelength of the input signal is equal to, or smaller than, the dimensions of the aggregate.

Harmonics

32. According to transducer theory, the pulse width of a one-half sine wave impact should be one-half of the period of the natural frequency of the crystal to produce maximum excitation of the crystal at resonance (Stein 1964). As an example, this means that a transducer would be highly sensitive if an impact from a steel ball on the concrete produced a 20-μsec-wide pulse, and the transducer had a resonance at 25 kHz ($f = 1/(2\ (20\ \mu sec))$). (The concrete slab would need to be much thicker than 3 or 4 in. to eliminate setting up a thickness resonance in the slab near 25 kHz and interfering with the measurement.) The preceding discussion refers to enhancing a pulse-echo condition in the concrete; not a resonance condition.

33. Spectrum-analysis tests on the impact load-pulse from the Schmidt hammer show the frequency content to follow the "bouncing ball" spectrum of a rectangular pulse (see the negative-going rectangular pulse in Figure 20 and the corresponding frequency spectrum in Figure 21). The width of the pulse (τ) is 100 μsec from an electrical pulse generator. The first null of the frequency content curve is at $1/\tau$ = 10 kHz ; the second null is at $2/\tau$ (20 kHz), etc. (Remember, as shown in Figure 12, that the frequency of the first null for a one-half sine wave is calculated differently than for a rectangular pulse and is 1.5 times the reciprocal of the pulse duration.) However, the frequency band of the highest energy exists from 0 to 5 kHz. The next main energy peak would be at 15 kHz, then 25 kHz, etc. We can see that there is a component of energy that exists at higher frequencies from the energy spectrum of the electronic rectangular pulse that could be used to excite a high-frequency crystal.

34. It can be seen that the broadband spectrum of energy from the impact of a rebound hammer can excite, for example, the 15th harmonic of a crystal. One could use a crystal having a fundamental resonant frequency of

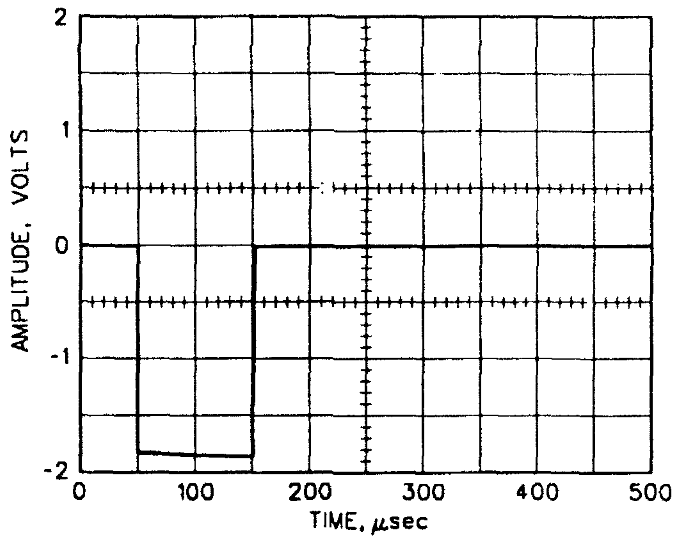


Figure 20. Rectangular shaped electrical pulse from a pulse generator (similar to shape of mechanical load-pulse from Schmidt hammer)

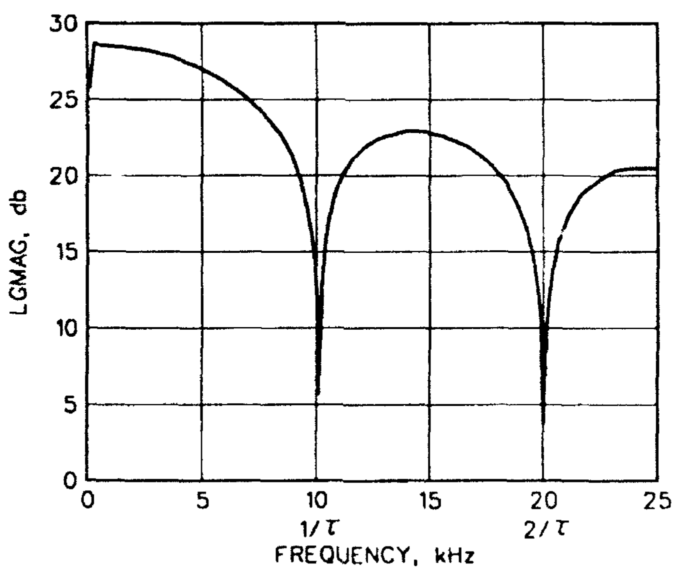


Figure 21. Frequency spectrum of rectangular pulse from a pulse generator

7,143 Hz (1/(2 (70 μsec))) and, by use of electrical filters, pass only the fifteenth harmonic of the crystal (107,000 Hz) through the recording system.

35. Piezoelectric plates vibrate in numerous fundamental modes with their respective harmonics when the crystal is excited (Krautkramer and Krautkramer 1977). An interesting fact that may be useful for impact-echo measurements is that: the Q, which is inversely related to the damping factor, decreases with the order of the harmonic. If the fundamental has a Q of 20, then the fifth harmonic would have a Q of 4. Since ultrasonic pulse-echo testing requires short pulses, it may be of benefit to pass only one of the higher frequency harmonics. All the harmonics of vibration are being excited by the broadband energy from an impact. Also, the sensitivity of each harmonic decreases as the order of the harmonic. Figure 22 shows a bandwidth measurement performed by exciting the PZT-C5500 transducer by an impact from dropping a steel ball on the faceplate of the transducer. Note that the fundamental is slightly less than 20 kHz, and harmonics occur at integral multiples of the fundamental.

36. An undamped transducer such as PZT will have too high a Q to permit ultrasonic pulse-echo measurements to be made through a penetration depth of less than a few feet when operating at the fundamental resonant frequency of the transducer. UPE measurements, whether for concrete or other materials, require low Q (wide bandwidth) transducers for proper operation. However, it is possible to perform ultrasonic pulse-echo measurements at one of the harmonic frequencies of the transducer since the Q decreases as the order of the harmonic (Krautkramer and Krautkramer 1977). If a transducer is excited by a gated sine wave pulse with the center frequency of the pulse at the resonant frequency of the transducer, the transducer will respond around that frequency only. If the transducer is shock excited with a very short impulse, it will respond at the fundamental resonant frequency and at all of its harmonics. One of the popular narrowband transducers used for through-transmission measurements in concrete is the James V-meter Model C-4898 transducer resonant near 54 kHz. The Q of the fundamental frequency is high, near 200, since the transducer is undamped. The twenty-fifth harmonic will have a Q of 200/25 or 8 as discussed. The frequency of the twenty-fifth harmonic will be 25 times the fundamental of 54 kHz or 1.4 MHz. The sensitivity of the harmonic also decreases in inverse proportion to the order

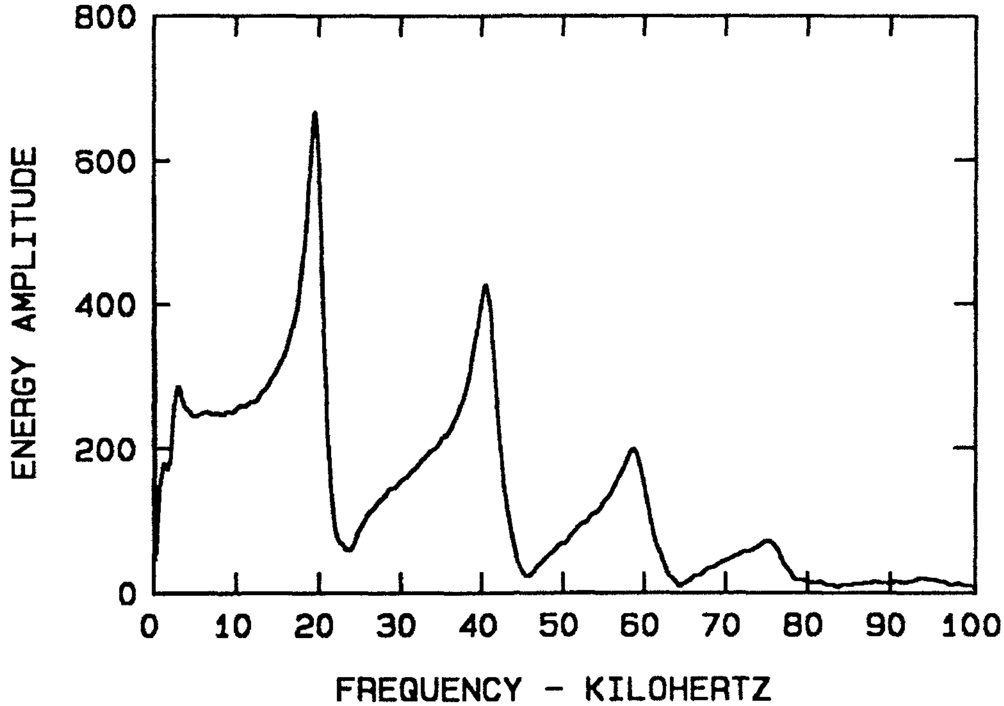


Figure 22. Frequency response of PZT-C5500 transducer from excitation by impact from a steel ball on the aluminum faceplate of transducer. Note the harmonics

of the harmonic. If the amplitude of the fundamental were 20 volts at 54 kHz, the amplitude of the harmonic at 1.4 MHz would be 20/25 or 0.8 volt.

37. The following test was made to verify the facts mentioned in the previous paragraph. A pitch-catch UPE measurement was made on a 6-in.-thick block of steel. The James V-meter transducer was used as the transmitter, and a low Q (≈3) transducer, Panametrics Model 301S, resonant at about 550 kHz, was used as the receiver. The transmitter was shock excited with the Panametrics Model 5055PR pulser with the damping control adjusted to get maximum response at a higher-frequency harmonic. High-pass filtering was performed both with passive and active filters to reduce the amplitude of the high-energy frequencies below 850 kHz. The first filter was a passive high-pass Model H62 by TTE, Inc., with cutoff at 200 kHz; next was an active high-pass filter from the Panametrics Model 5055PR, with cutoff at 500 kHz; an amplifier followed with a gain of 60 db on the filtered signal; a Wavetek Model 442 active band-pass filter followed that, with cutoff at 850 MHz; a

rolloff attenuation of 48 db/octave, and a stop-band attenuation of 80 db. Multiple echoes were received with a duration of 51 μsec between echoes with the spectrum of the echoes having the main energy at about 550 kHz and 1.2 MHz. See the echoes in the time domain in Figure 23 and the echoes in the frequency domain in Figure 24. The peak at 550 kHz is larger than the 1.2 MHz peak due to the fact that the transducer receiver is more sensitive at that frequency, although the lower frequency received some filtering. The following observations were noted. Surface waves which normally would have been present at the low frequency of 54 kHz and would have totally prevented the detection of echoes have been eliminated by operating at a higher frequency. The twenty-fifth harmonic has a Q of about 8 and is not too high for making UPE measurements through a penetration depth of less than 1 ft in a small-grain material, since the wavelength is so short at that frequency. However, the attenuation in concrete is simply too high to permit a UPE measurement at 1.2 MHz as was done in the metal. This test illustrates that pulse-echo measurements are at least possible with a high Q (narrowband) transducer by operating at one of the harmonics of the fundamental.

38. To illustrate the potential of harmonic operation, assume that the thickness of a section of concrete floor slab is being measured. The round-trip time of a longitudinal pulse for a thickness of 9 in. is about 100 μsec. For proper resolution, the pulse length should not be longer than one-tenth of the path length (10 μsec or less). Assume that we are using an undamped transducer with a resonant frequency of 20 kHz for the fundamental mode. If the fundamental had a Q of 22, then the eleventh harmonic would have a Q of 2 (as discussed) and, once excited, would ring for about two cycles before dying. At a frequency of 220 kHz (eleventh harmonic), the two-cycle pulse would be slightly less than 10 μsec and that meets the proper criteria.

39. If a different concrete structure is chosen and the thickness of the concrete is 900 in., this is an increase in travel path of 100 times over the first case. The round-trip time of the longitudinal pulse in the concrete would now be 10,000 μsec. For proper resolution, the pulse length could not exceed 1,000 μsec. If the imaginary band-pass filter is moved and it passes the fundamental frequency (first harmonic) only, it has a period of 50 μsec and will ring for about 22 cycles. That corresponds to a pulse length of 1,100 μsec. That may be a little longer than desired, and proper resolution

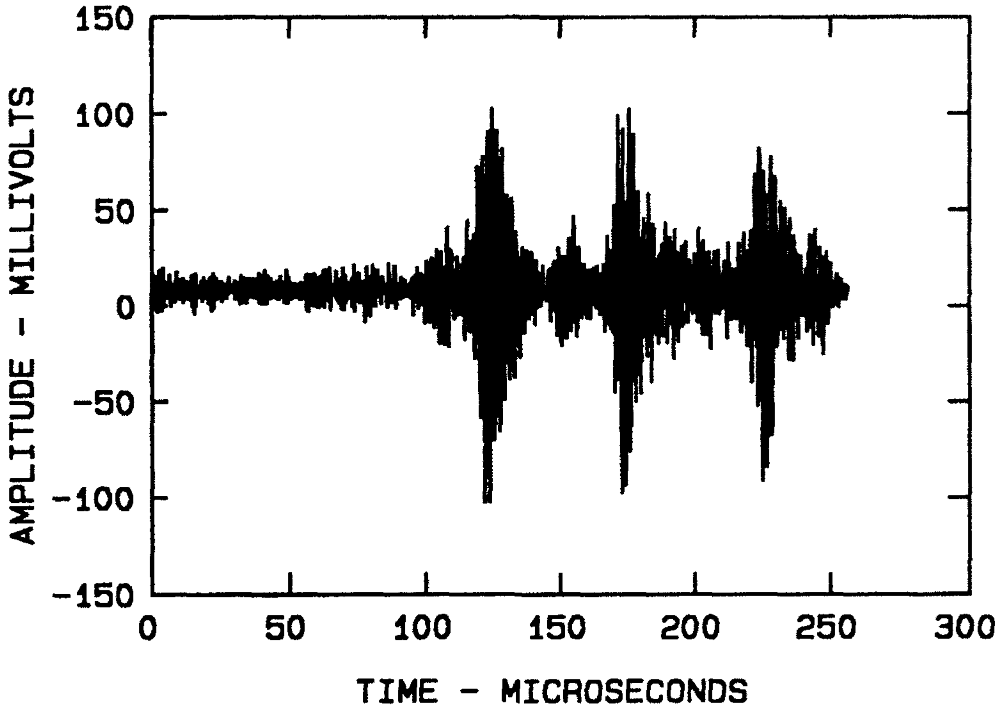


Figure 23. Ultrasonic pulse-echo measurements on a 6-in.-long steel block with all frequencies below the tenth harmonic of a 54-kHz narrowband transducer highly attenuated by filtering

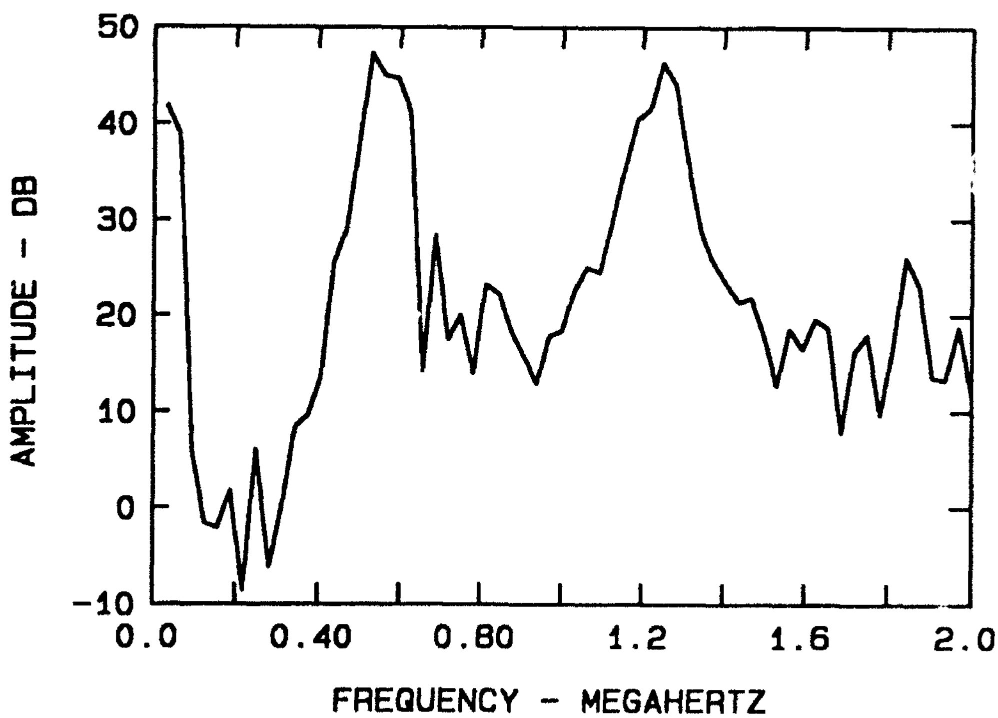


Figure 24. Frequency spectrum of previous echoes shows that the primary energy accepted through the recording system is near 550 kHz and 1.2 MHz

can be reached by moving on to the second or third harmonic. Notice, however, that the operation of the piezoelectric plate corresponds to the resolution and sensitivity needed for the particular thickness measured in the concrete. That is, when thickness is short and more resolution and less penetration is required, a higher frequency harmonic can be passed. When the distances are long and less resolution and more penetration is needed, one can pass a lower-frequency harmonic or possibly the fundamental. This remains to be tested in concrete.

Digital Signal Processing

40. A software package, Computer-Aided Circuit Analysis, Optimization, and Measurement (COMTRAN), was designed for AC circuit analysis by Jensen Transformers, Inc. This software was used in conjunction with a Hewlett-Packard (HP) series 300 computer and a HP 5182A waveform recorder to acquire impact-echo response signals in the time domain and compute the Fast Fourier Transform (FFT) of the signals. The software package was capable of performing Fast Convolution as shown in Figure 25, as well as many other digital signal processing (DSP) techniques.

41. A small computer program was written to generate digitized echoes having a user-defined center frequency, a constant time between echoes, and a fixed attenuation of multiple echoes. Another program was modified from another computer language to compute a digital band-pass filter in the HP Rocky Mountain Basic language. The filter was capable of being adjusted to various cutoff frequencies both above and below the center frequency.

42. Figure 26 shows a series of mathematically calculated echoes occurring every 128 μsec with the transducer having a center frequency at 50 kHz. An FFT of the time domain signal in Figure 27 shows the energy centered about 50 kHz with various harmonics separated by the difference frequency of 7.8 kHz. The envelope of the waveform represents the frequency response of the transducer while the "comb" pattern is due to the echoes. The difference frequency of 7.8 kHz (difference between "teeth" of "comb") is the reciprocal of the time between echoes, 128 μsec. See paragraph 14.

43. One of the signal processing operations that COMTRAN will perform is convolution. The counterpart of convolution in the time domain is complex

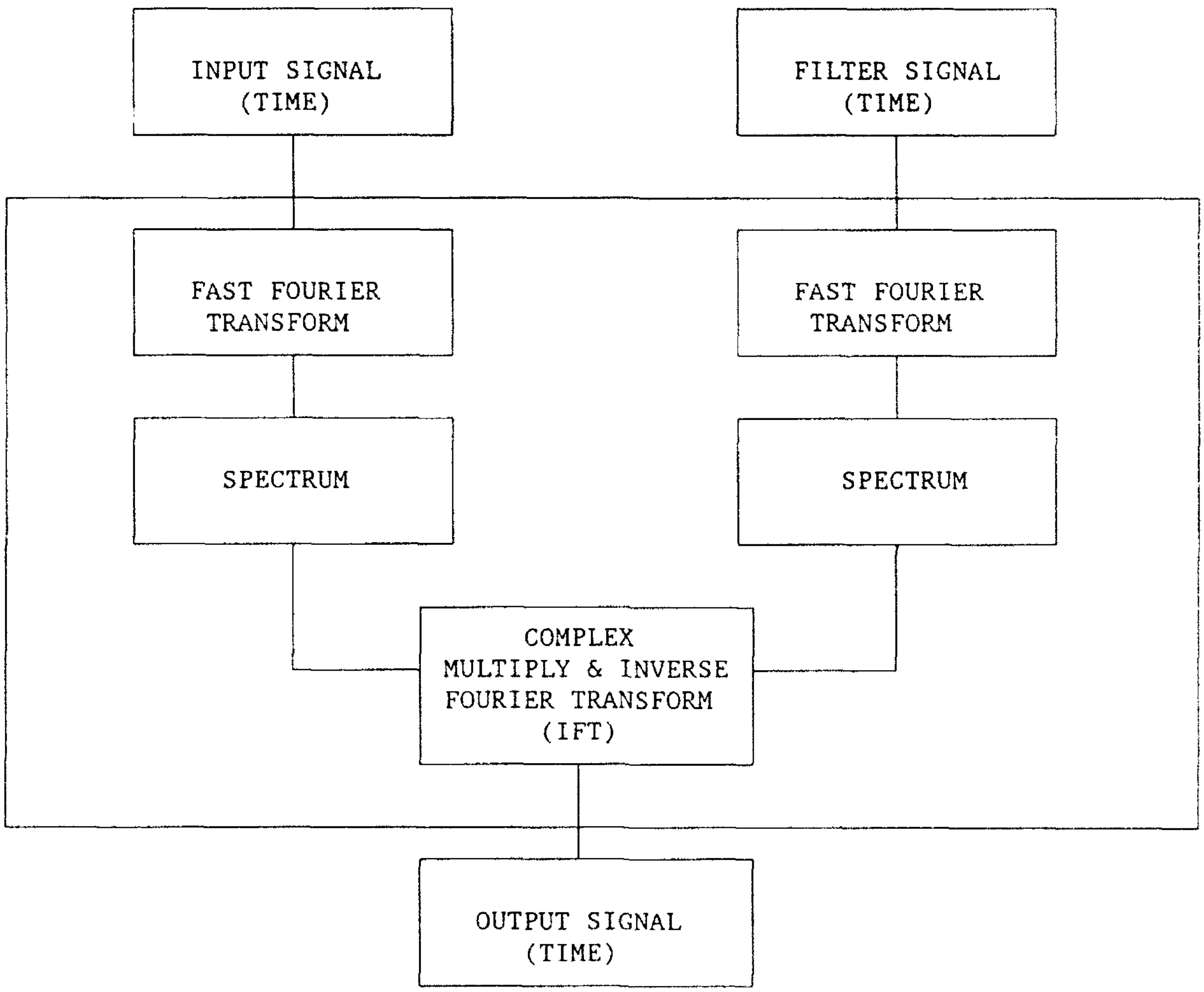


Figure 25. Illustration of method to perform digital filtering. This is sometimes called "Fast Convolution"

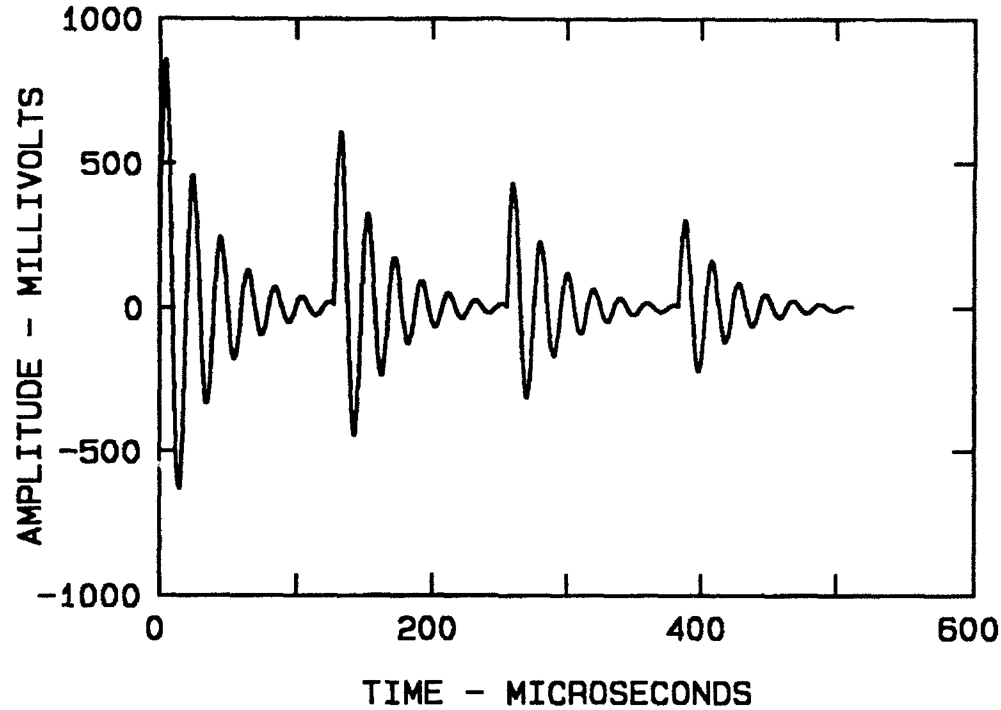


Figure 26. Echoes generated mathematically to simulate possible action in concrete. The center frequency of the transducer is 50 kHz and the echoes occur every 128 μsec

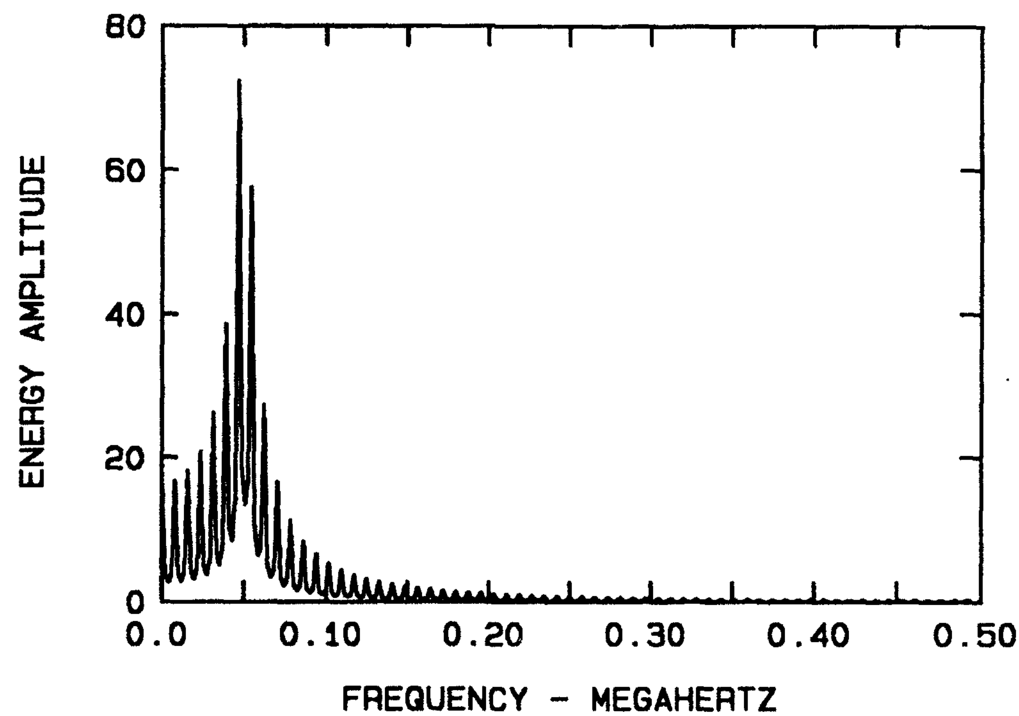


Figure 27. FFT (Spectrum) of previous echoes. Spacing of frequency peaks is 7.8 kHz or reciprocal of times of arrival of echoes of 128 μsec

multiplication in the frequency domain. In the time domain, the input signal is convolved with the impulse response of the filter to generate the output signal, also in the time domain. If the FFT is taken of the input signal and complex multiplied by the FFT of the filter's impulse response (frequency response function of filter), one will obtain the output signal in the frequency domain (same as the FFT of the output signal gotten by convolution in the time domain). So convolution in the time domain is equivalent to complex multiplication in the frequency domain. Equation 10 shows the convolution process in the time domain

$$V(t)_o = V(t)_i * I(t) \tag{10}$$

where

$V(t)_i$ = input signal in the time domain

$I(t)$ = impulse response of the filter in the time domain

$V(t)_o$ = output signal in the time domain

Equation 11 represents the convolution process in the frequency domain

$$S(f)_o = S(f)_i F_r(f) \tag{11}$$

where

$S(f)_i$ = input signal in the frequency domain

$S(f)_o$ = output signal in the frequency domain

$F_r(f)$ = frequency response of the filter

44. A high-pass digital filter was computed that only passed energy above 25 kHz. This is shown in Figure 28 as the impulse response of the filter. The FFT of the impulse response yields the frequency response function shown in Figure 29. This view of the filter is more informative as it is clear that the filter only passes information above 25 kHz. Figure 30 is the result of convolving the signal, Figure 27, with the filter. All frequencies below 25 kHz have been attenuated. By doing an inverse FFT on the result as shown in Figure 31, the sharpness of the front of the echoes has been reduced somewhat, and the pulse has been lengthened due to the low frequency filtering.

45. The point to be made is that the large, spurious low frequencies created by an impact could be filtered from the composite signal without destroying the desirable higher frequencies. Because the bandwidth must be

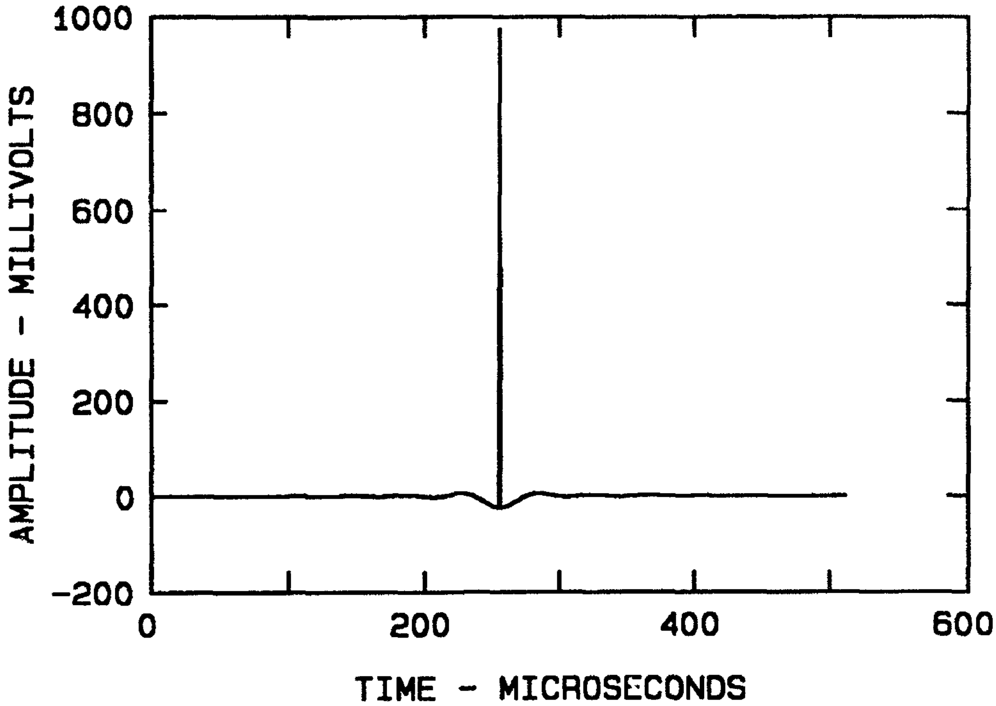


Figure 28. Impulse response of a high-pass digital filter with cutoff at 25 kHz

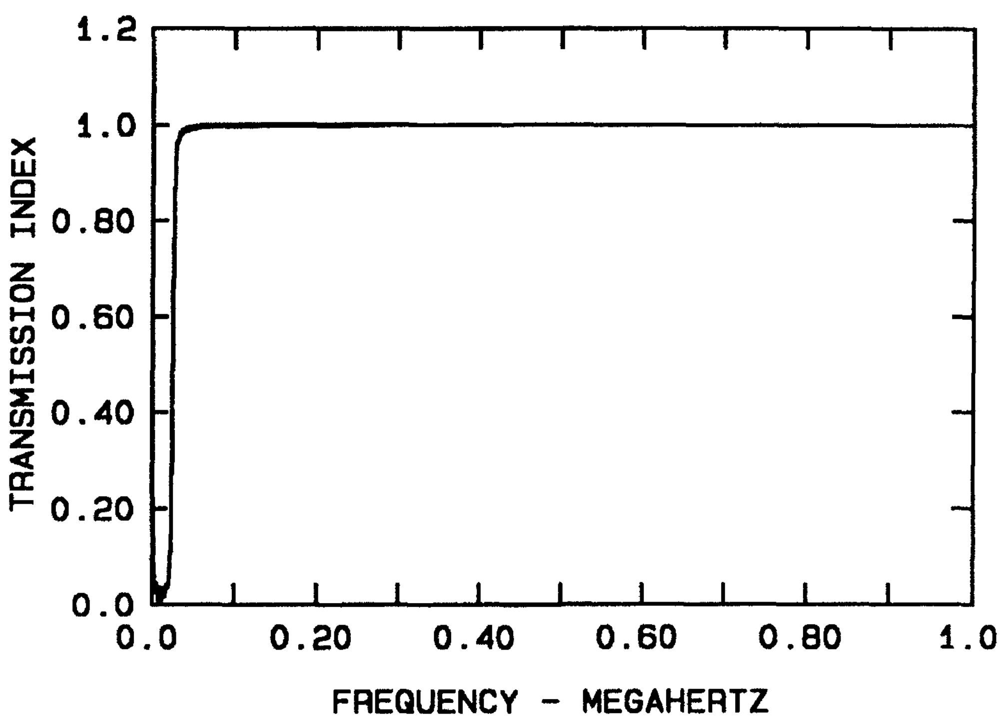


Figure 29. Frequency response of digital filter showing cut-off at 25 kHz

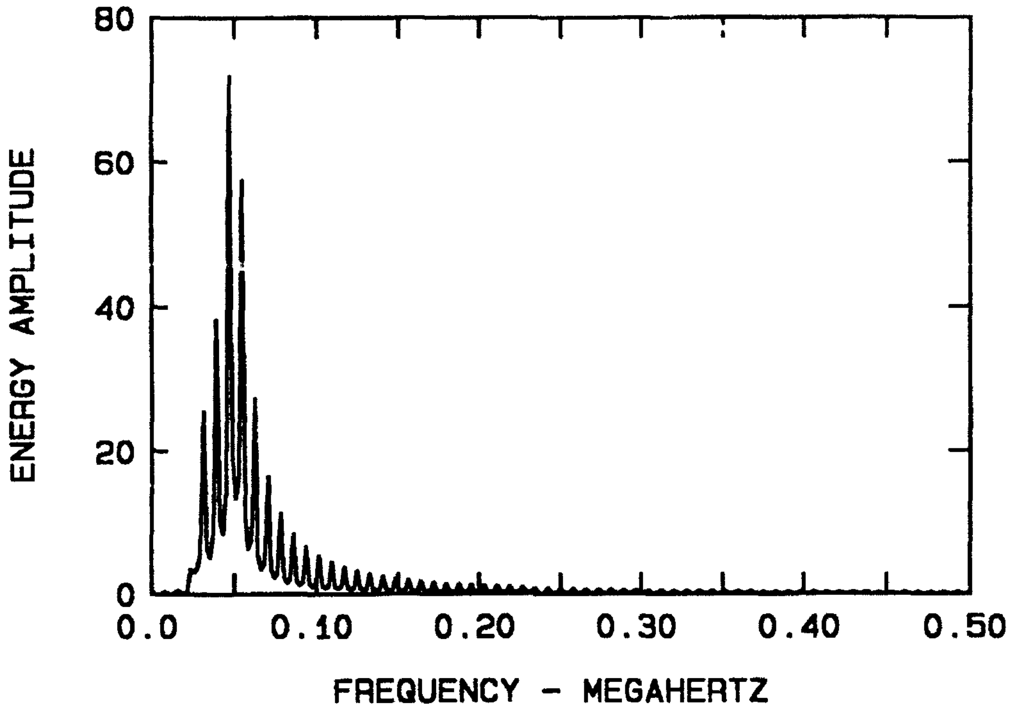


Figure 30. Resulting frequency response after convolving time-domain echo signal with impulse response of filter. Note the attenuation of energy below 25 kHz

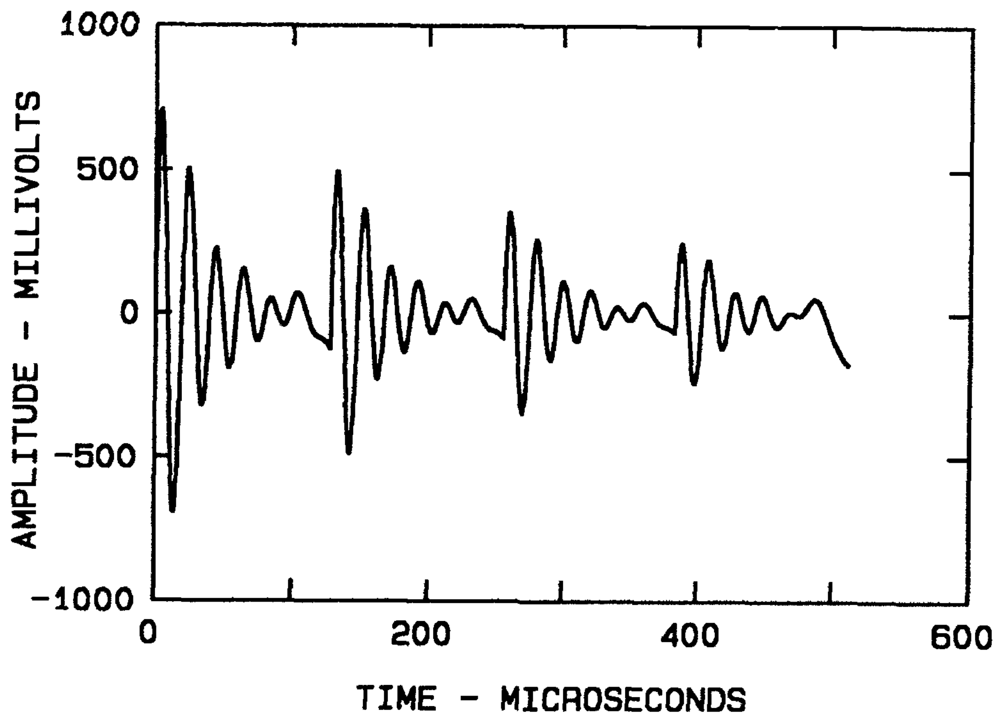


Figure 31. Inverse FFT of previous signal showing that echoes can be seen after the attenuation of the low-frequency energy by filtering

adequate to pass the high-frequency components and yet reject the extraneous low frequencies that necessarily occur when an impact on concrete is made, it is probably better to use a high-pass filter rather than a band-pass filter.

Bandwidth Considerations

46. The designer of a digital filter must consider information about the signal's bandwidth if it is desired to reproduce the desired signal accurately. An adequate bandwidth is especially important when transmitting short pulses. Yet, since an impact excites so many extraneous modes of vibration, it is important that the bandwidth be kept to its smallest possible value to prevent interference from undesired signals. If some of the important component frequencies are suppressed by the electrical system, then the transmission distorts the pulse and, in particular, lengthens it. To transmit a pulse of duration T, a frequency bandwidth of $B = 1/T$ is sufficiently wide to pass the pulse without considerable distortion even if the amplitude of the frequencies passed on either end of the band is only 70 percent of that passed at the center of the band (Krautkramer and Krautkramer 1977).

47. A filter with a bandwidth of 100 kHz, therefore, could transmit with practically no distortion a pulse of 1/100 kHz = 10-μsec duration, e.g. five oscillations of a 500-kHz frequency (period is 2 μsec). Any pulse is a complex wave, containing many sine-wave components. If the pulse is repetitive, then the lowest-frequency component, the fundamental frequency, is exactly equal to the pulse repetition rate. The other components are harmonics of this value (DeFrance 1963). For example, a pulse with 10-μsec duration and a repetition rate of 10 kHz (approximate longitudinal echo rate in a 9-in.-thick concrete slab) would contain frequency components from 10 kHz to at least 600 kHz. But, as explained, one could reproduce the pulse with a fair degree of accuracy with a 100 kHz-bandwidth centered at 500 kHz.

48. The rise time of a rectangular shaped pulse determines the highest-frequency component present in the pulse. (This is a common method to test the bandwidth of a hi-fi system.) A system will ring at its resonant frequency when excited by a rectangular pulse sufficiently short in duration to contain energy at that frequency. There is no build-up time required for

the system to respond with maximum amplitude, such as is the case when the system is excited by sine-wave bursts at the resonant frequency of the transducer. If the Q of a transducer is equal to 2, it will take two cycles of a sine-wave stimulus for the transducer to reach 96 percent of its maximum amplitude. However, with shock (impulse) excitation, the transducer will reach its maximum amplitude in a fraction of one-quarter of a cycle of the transducer resonant frequency (Hueter and Bolt 1955). This is an important factor to understand when measuring the exact TOA of an echo. The front of the pulse will be sharp and will have maximum amplitude for shock excitation.

49. There is still another factor in the consideration of bandwidth. Since concrete is a highly attenuative material, it will tend to act as a mechanical low-pass filter on the higher frequencies and distort the pulse. It may be necessary to provide equalization by means of an electrical network to boost the high-frequency components in conjunction with the high-pass filter previously discussed. It is necessary to pass the high-frequency harmonics of a pulse to prevent distortion and lengthening.

PART III: LITERATURE REVIEW

Impact Measurements Research

50. The load-pulse duration from a hammer impact does not necessarily correspond with the period of longitudinal resonance of the concrete when making impact-echo measurements as is the case with impact-resonance measurements (Alexander 1991). The width of the load-pulse (contact time) should be equal to one-half of the period (T) of the longitudinal resonant frequency in the concrete to cause maximum response when making resonant-frequency measurements. However, it is necessary that the contact time of the hammer be no more than 10 percent of the two-wave travel time in the concrete to properly resolve echoes for impact-echo measurements. If the pulse duration is equal to 1/2 T, it would create a resonant condition rather than a pulse-echo signal. A number of sinusoidal reverberations are generally measured for a resonant condition which is effectively an averaging process. If the pulse duration is less than 10 percent of the period, then a pulse-echo condition will dominate over a resonance condition and only one echo must be detected for a proper measurement.

51. In 1981, the author impacted a 200-lb mass against an insitu concrete pier having a mass of about 1,000,000 lb on the Lake Superior Control Structure near Sault Sainte Marie, MI (Alexander 1981). It was possible to resonate the structure in its flexural mode. Although that investigation demonstrated the potential of impacts to make resonant-frequency measurements, this report primarily deals with pulse-echo measurements.

52. Howkins (1968) used a 40-in. steel rod with the top end case hardened to receive a small steel ball shot from an air gun. He was able to produce a pulse as short as 10 μsec. He used a condenser microphone (ultramicrometer) as a receiver. The receiver was designed for the low acoustic impedance of air and, therefore, presented a serious mismatch with the acoustic impedance of concrete. The system was subject to noise as the sensitivity of the microphone was very low. However, he measured the thickness of a 10-in. slab of concrete using the impact-echo technique.

53. Sanasalone and Carino (1986) have developed an improved impact resonant-frequency system for detecting interfaces in concrete. Small steel

balls with diameters of about 3/8 in. and larger are used to generate energy primarily in the sonic range (< 20 kHz). Sinusoidal reverberations are measured with a sensitive, broadband receiver. It will penetrate to a depth of a few feet.

54. Muenow has developed an impact-echo system for which details have not been made public except in a general sense (Muenow 1990). Although the claims of the system are significant, not enough is known about the system to evaluate its accuracy and to verify the physics of the measurement.

55. Desai et al. (1974) tested a large dam in India for cracks by an impact-echo technique by dropping a large-diameter (dimensions unknown) steel ball on the top surface and detecting echoes from a crack plane estimated to be 15 m across. The frequency of the energy was estimated to be in the low end of the sonic range at about 240 Hz. The actual depth of the crack is not known.

Sonic Impact Pulse-Echo Research

56. Sonic pulse-echo tests were made on a pile 80 ft long and 14 in. square in cross section and lying on the soil (Alexander 1980). Figure 32 shows the concrete pile, sledge hammer, and transducer used to make pulse-echo measurements. A 12-lb sledge hammer was used to impact the end of the pile. The reflection was received with a James Electronics, Inc., Model C-4966 transducer with resonance near 50 kHz. Operation took place in the broadband region of the transducer response curve below resonance. No filtering or signal processing was required. Figure 33 shows the cracked pile and Figure 34 presents the echo signal. The load-pulse can be seen at the time of impact and also four reflections from a crack located 16.2 ft from the impact end of the pile. Since the location of the crack is about 20 percent of the length of the pile, five reflections will occur from the crack and arrive at the transducer before the reflection arrives from the opposite end of the pile. The large reflection arriving at a point located about 2/3 of the way along the x-axis is the load-pulse reflecting off the opposite end of the 81.625-ft-long pile. Two more echoes are seen on the trace from the crack as the energy continues to reverberate in the pile.

57. The load-pulse introduced into the concrete is about 1.2 msec long.

Figure 32. 80-ft-long concrete pile, sledge hammer, and piezoelectric receiver used in making a sonic pulse-echo measurement

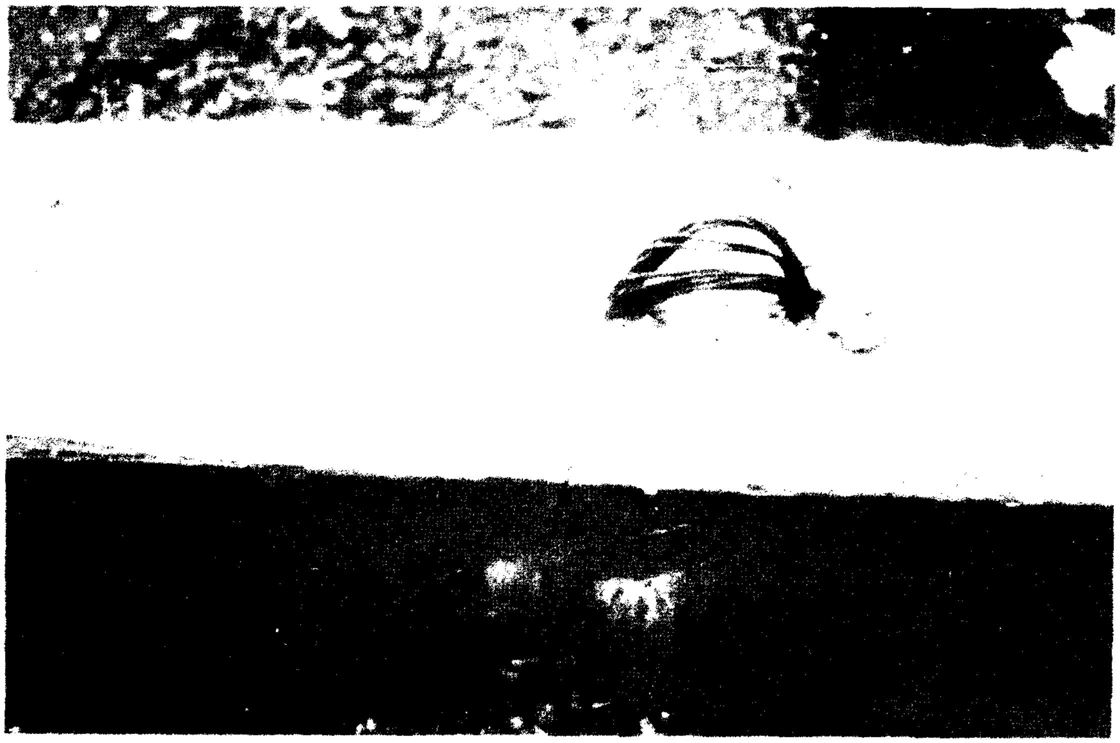


Figure 33. Crack in pile located 16 ft from end of pile

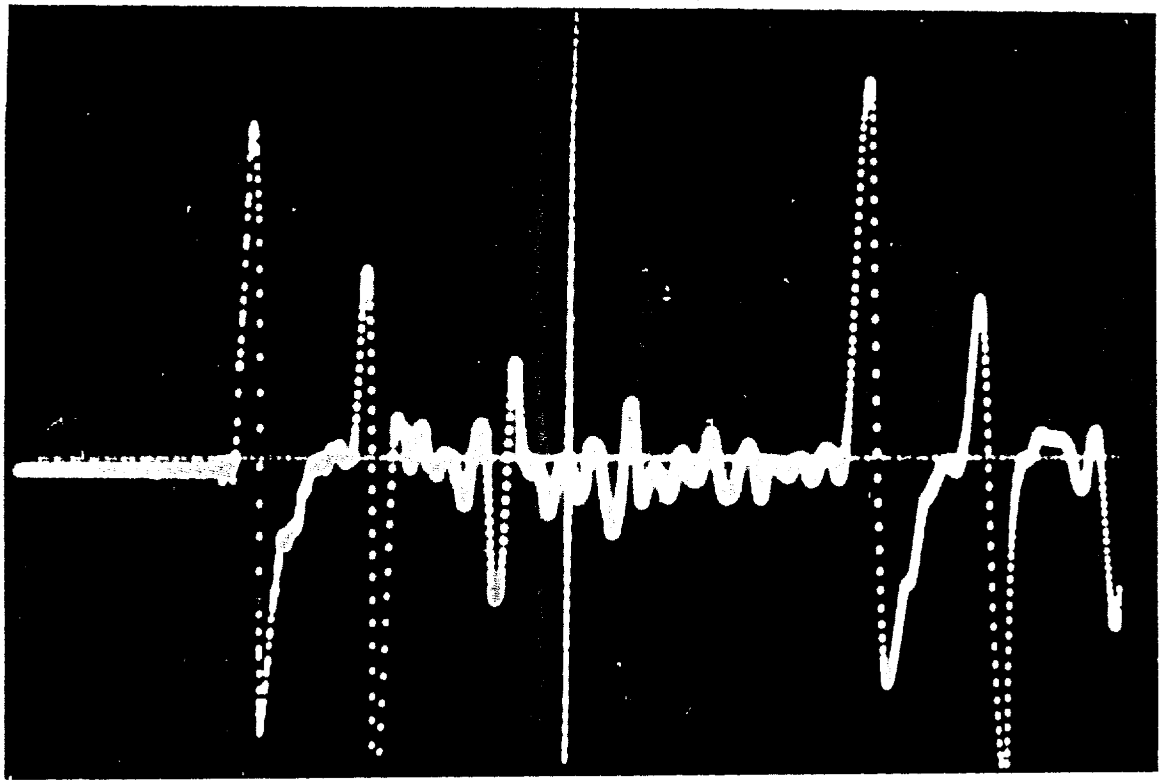


Figure 34. Arrival of echoes from end of pile and from crack. Five echoes can be seen from crack before the large amplitude echo arrives from the pile end

This corresponds to energy existing primarily at a frequency of about 833 Hz. The first dip in energy would occur at 1,250 Hz as described earlier in this report. The total travel time down and back the length of the pile is 11.46 msec for the 14,245 ft/sec longitudinal-velocity wave. So the pulse length in units of time is about 10 percent of the round-trip time for the pulse in the concrete pile.

> "In setting up the pulse system, the length (distance) of the pulse should be adjusted according to the minimum distance of transmission. For example, if an operator were testing a part that was 1 in. thick, he would want the pulse to be a very small fraction of an inch. The time it takes for ultrasonic waves to travel 1 in. in steel or aluminum is about 8 μsec; so a good length for the pulse would be 2 μsec. If he were testing a part that was 20 ft long, the operator could have a pulse length of 5 to 10 μsec. This longer pulse enables him to get somewhat more power into the medium and therefore greater penetration." (Carlin 1960)

In this case the pulse length is 17 ft long or about 10 percent of the 163.25-ft round-trip travel path in the pile. In most cases, the pulse length should not be more than 10 percent of the total round-trip travel time for the pulse for impact-echo measurements to obtain the proper resolution. The pulse can be longer for impact-resonance measurements. This report is primarily concerned with ultrasonic pulse-echo measurements by impact.

58. For a typical concrete pavement thickness of 9 in., the round-trip travel time is about 100 μsec. Therefore, the pulse length should not be much longer than 10 μsec to properly resolve echoes. One cycle of a sinusoidal pulse would correspond to a center frequency of 100 kHz. Since the upper frequency limit for concrete is close to 200 kHz, to prevent excessive scattering, the pulse length could not be much shorter than 5 μsec ($T = 1/200$ kHz). This represents a fairly narrow window (5 μsec $<$ pulse length $<$ 10 μsec) for measuring thickness or locating flaws in concrete pavements and floor slabs using impact-echo measurements.

59. The long slender pile acts as a waveguide to keep the energy contained within the pile. However, with a slab the energy spreads out in all directions with only a small percentage of the original energy reflecting from the base of the slab. This makes the slab measurement much more difficult than a pile measurement.

PART IV: LABORATORY WORK ON BROADBAND TRANSDUCERS

Using Resonant Transducers as Broadband Receivers

60. To accurately reproduce the shape of transients with an undamped (resonant) transducer receiver, it is necessary that the natural period of the transducer be much lower than the width of the transient pulse being measured. This ensures that operation will occur in the broadband portion of the frequency-response curve of the transducer and that the pulse will not cause the transducer to resonate. With one-half sine or triangular shaped transients, the transducer's natural period should be less than one-fifth the pulse duration (Stein 1964) for faithful reproduction.

61. This becomes much more critical with short, square transients like one produced by sharp impacts from a Schmidt rebound hammer. A typical impact waveform from the rebound hammer impacting a load cell on concrete is shown in Figure 35. The trace is load versus time, and the width of the main load pulse is about 70 μsec. A wider pulse will be created from an impact on concrete because the concrete is softer than the metal load-cell. However, the rise time will still be sharp when the hammer impacts the concrete directly. A typical rebound hammer is shown in Figure 36.

62. With these sharp impact pulses, the rise time of the pulse becomes the determining criterion that creates the high-frequency energy rather than the pulse width as is the case with the sine wave. If the rise time is short in comparison with the pulse width, as much as 100-percent overshoot is present (caused by subsequent excitation of the transducer natural period). If filtering is not used to attenuate the ringing, then it is desirable for the transducer to have a natural period of one-third the rise time, or less. If it takes 5 μsec for a 70-μsec-wide pulse to rise, then a resonant transducer with a natural period of 1-2/3-μsec, or less, would be required to accurately reproduce the pulse without ringing and overshoot. That corresponds to a transducer having a resonant frequency of 600 kHz.

63. In summary, a transducer must have much shorter natural period to reproduce the actual shape of a rectangular pulse than is required to reproduce a half-cycle sinusoidal pulse. Or, equivalently, the resonant

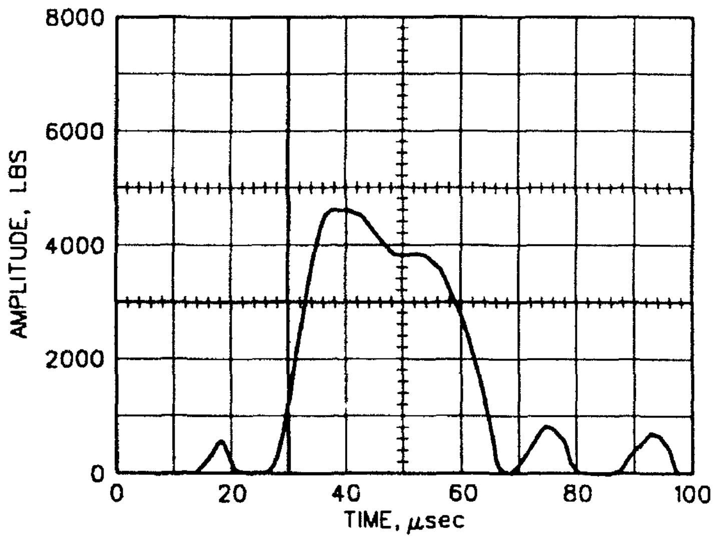


Figure 35. Typical load-pulse produced from impact on concrete with a Schmidt rebound hammer. Pulse is about 70 μsec wide with amplitude near 5,000 lb of force. Rise time is less than 10 μsec

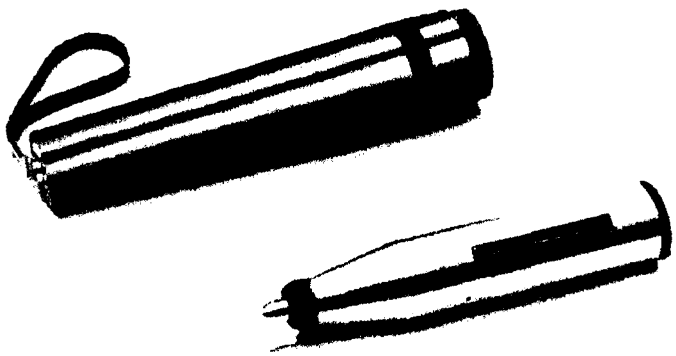


Figure 36. A typical model of a Schmidt rebound hammer traditionally used to measure the rebound number of concrete (ASTM C 805) (ASTM 1992). In this investigation it was used to generate stress wave energy for ultrasonic pulse-echo measurements

frequency of the transducer must be much higher to reproduce rectangular pulses than to reproduce sinusoidal pulses.

PZT-Steel Rod Transducer and Rebound Hammer

64. Figure 37 shows the first impact-echo transducer built at the US Army Engineer Waterways Experiment Station (USAEWES) for use on concrete. A piezoelectric element was bonded to a steel rod 7 ft long and 1/2 in. in diameter. A 1/2-in.-diam PZT element, about 1/16 in. thick and initially resonant at 1.2 MHz while unbonded, was bonded with silver epoxy to the lower end of the rod. A short piece of rod 1-1/2 in. long was bonded to the other face of the crystal. It took 840 μsec for a longitudinal pulse to travel from the piezoceramic to the top of the rod and back to the crystal. This allowed enough time to receive a number of echoes from the 9-in.-thick slab shown in the photograph before the pulse emanating from the back side of the crystal could return and interfere with the pulse that left the front face of the crystal. The two-way travel time in the slab was 102 μsec. The energy was introduced into the slab with a Schmidt hammer (Figure 36). Initially, to increase the introduction of high frequencies into the concrete, a piece of 1/4-in.-thick steel was bonded to the surface of the concrete, and the impact was made on the steel plate. The sonic pulse-echo measurement is shown in Figure 38. At least three echoes can be seen at 100, 200, and 300 μsec. The top of the waveform is clipped as the input amplifier is being overdriven due to the high-amplitude acoustic energy from the hammer. This Hopkinson Bar type of transducer demonstrated that measurements can be made when a sensitive broadband receiver is available. However, the long rod is not practical for field work and would probably never be feasible for detecting interfaces in concrete. In Figure 39, a pulse-echo measurement is shown where an impact was made directly on concrete, remote from the steel plate. The TOA is approximately 100 μsec. The rise time is obviously too slow for making an accurate thickness measurement. However, the measurement may be satisfactory over a longer penetration depth.

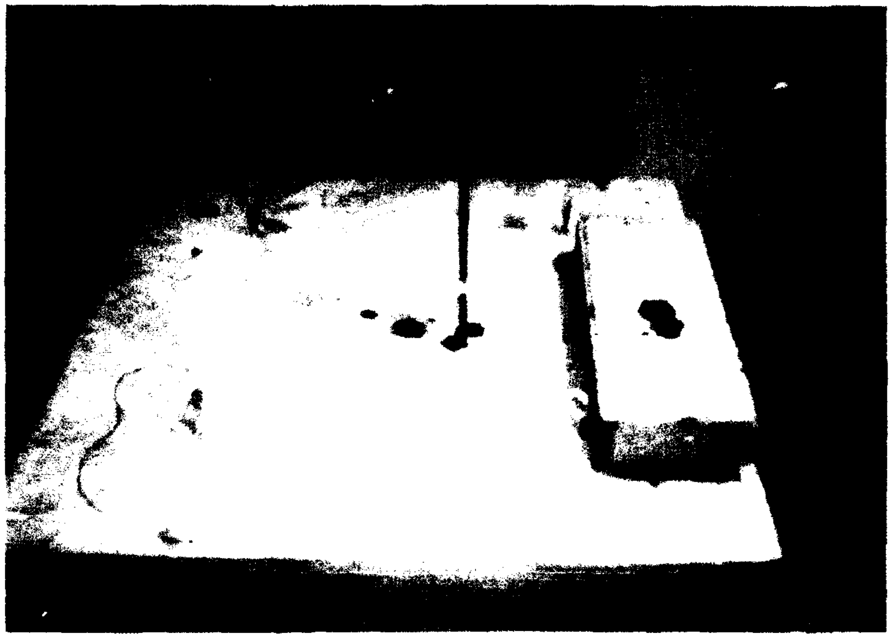


Figure 37. PZT piezoelectric element bonded to end of 7-ft steel rod used to make pulse-echo measurements on concrete slab. Analogous to function of a Hopkinson Bar

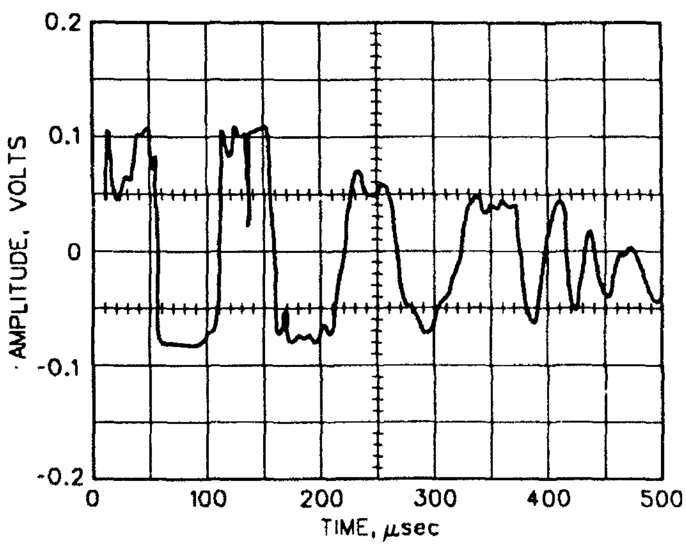


Figure 38. Echoes from concrete slab detected with PZT-steel rod transducer. Impact made on steel plate bonded to concrete surface

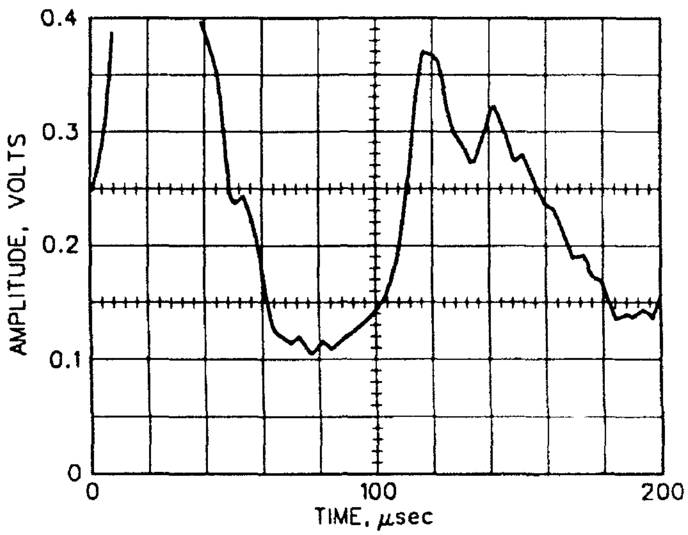


Figure 39. Echoes from concrete slab detected with PZT-steel rod transducer. Impact made directly on concrete surface

PZT-Steel Rod Transducer and Shot Pellet (BB) Pistol

65. At this point, measurements of the reflected impact pulse showed that it lacked the necessary rise time and sensitivity for the accuracy needed in pulse-echo measurements in concrete for thin sections. Too much of the energy was in the sonic range rather than the ultrasonic range. In other words, a much shorter load-pulse was needed with higher intensity. An air pistol that shot standard commercial pellets was obtained. The small projectiles were fired onto a steel plate epoxied to the surface of the concrete. Successful measurements were made on a 3-in.-thick slab using the steel rod transducer. However, even though the impact pulse was about 20-μsec wide, the measurements lacked sufficient accuracy. Since the first dip in the frequency spectrum would occur at 75 kHz, as explained in Part II, the main energy would lie below that value. Steel balls, which are much harder than the air gun pellets, might yield shorter load pulses. This was not tested.

PZT Aluminum Rod Transducer

66. Another rod transducer was built, this time, from aluminum. It also consisted of a PZT element resonant at 1.2 MHz, before damping. The acoustic impedance of aluminum is closer to concrete than steel, and it was hoped this might improve measurements. Also, the rod was only about 3 ft long as compared with the steel rod of 7 ft. No significant improvement was noted.

James V-meter Transducer and Lead Backing

67. A mosaic of PZT elements taken from a James Electronic's transducer resonant at 54 kHz, shown in Figure 40, was used with a backing of epoxy mixed with lead powder. The transducer was 20 in. long and weighed 35 lb. The idea was to terminate the back side of the crystal in its own characteristic impedance with the backing sufficiently long and sufficiently attenuative to totally prevent reflections. This would allow the transducer to be shorter in length than the rod transducers and field-worthy. Here, the idea was to match the backing with the PZT in its acoustic impedance so that the transmission

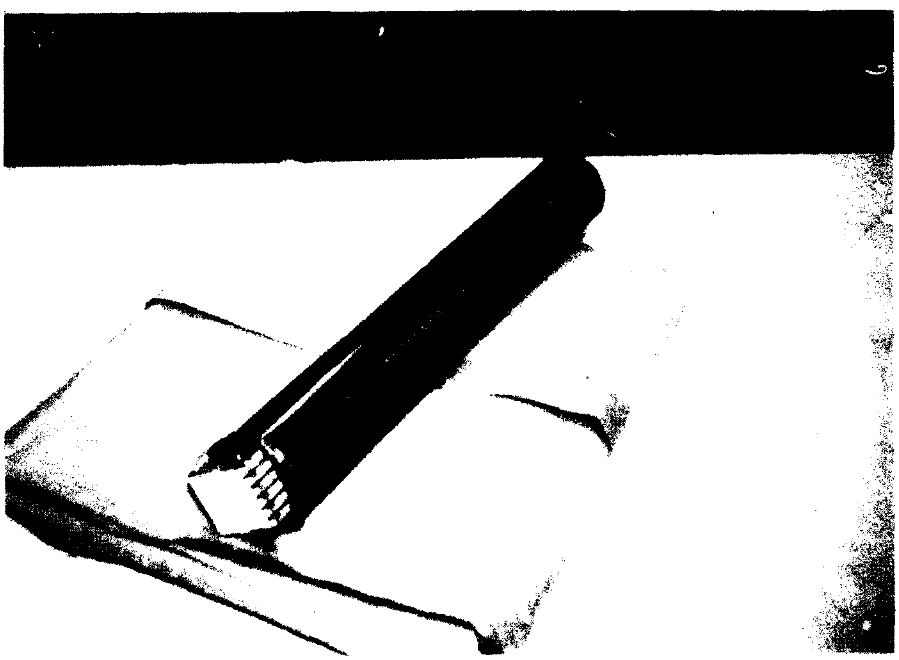


Figure 40. PZT mosaic transducer with epoxy/lead backing

coefficient was high at this interface. Once all the energy was introduced into the backing without reflections at the interface, it was hoped that enough lead was added to the crystal backing to dissipate the energy before it could reflect from the back surface of the backing and return to the crystal. Bandwidth curves are shown of the transducer mosaic before and after damping. Figures 41 and 42 illustrate the frequency characteristics of the undamped and damped transducer, respectively.

68. Obviously, the damping was successful (as far as the response being made flat) throughout the frequency range of interest. However, the sensitivity was reduced considerably by the damping. The sensitivity was reduced more than was necessary as the lead/epoxy backing produced a partially shorted path for the output voltage at the interface where the ceramic crystals were molded into the backing. Earlier experiments had shown that a larger grain combined with epoxy had high electrical insulation properties. This was not the case with this 150 μm (No. 100 sieve) powder. The thickness measurement on the 9-in. slab is shown in Figure 43. A low-pass filter was used to pass frequencies below 10 kHz.

Underwater Explosive Measurements on Concrete

69. Impact pulse-echo measurements were made underwater over a 4-ft-thick concrete slab. The stress waves were generated by small explosive charges. The tests were made in a shallow water basin about 100 ft square with 4 ft of water over a 20- by 40- by 4-ft concrete slab. Charges of 0.87 g (cap only), 22 g and higher levels provided the source of stress wave energy. However, pulse-echo signals were obtained only with the 0.87- and 22-g source. The depth of the charge and pressure gages were all 3.5 ft below the surface of the water (0.5 ft in height above the surface of the concrete slab). Numerous pressure gages were located in a line at various horizontal distances from the location of the charge, but only the results are shown in Figure 44 for the sensor located at a separation distance of 1.28 ft. The charge mass was 0.87 g. The charge was an RP-83 EBW detonator manufactured by Reynolds Industries, Inc. The detectors of the stress waves were Model PCB138A10 tourmaline pressure gages, resonant at 1 MHz and with a range of

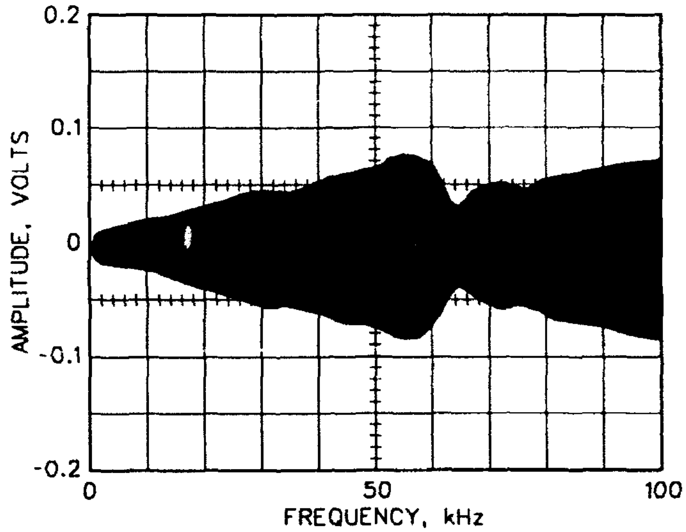


Figure 41. Bandwidth of a PZT mosaic transducer, undamped

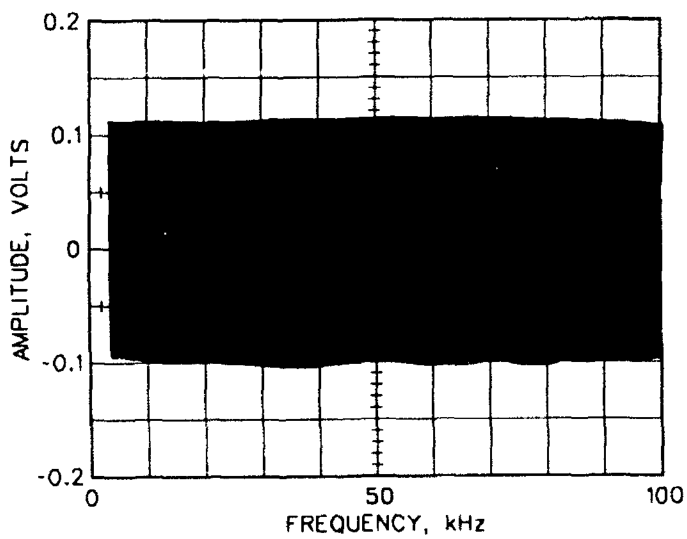


Figure 42. Bandwidth of a PZT mosaic transducer, damped

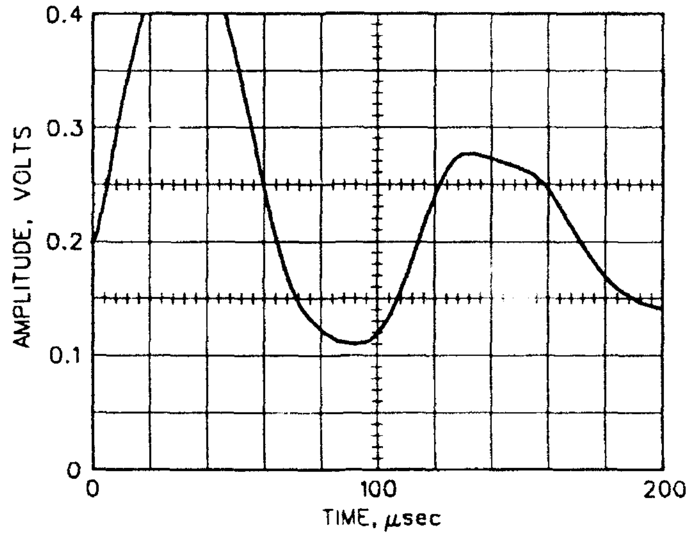


Figure 43. Thickness measurement on 9-in.-thick concrete slab with PZT epoxy/lead-backed transducer

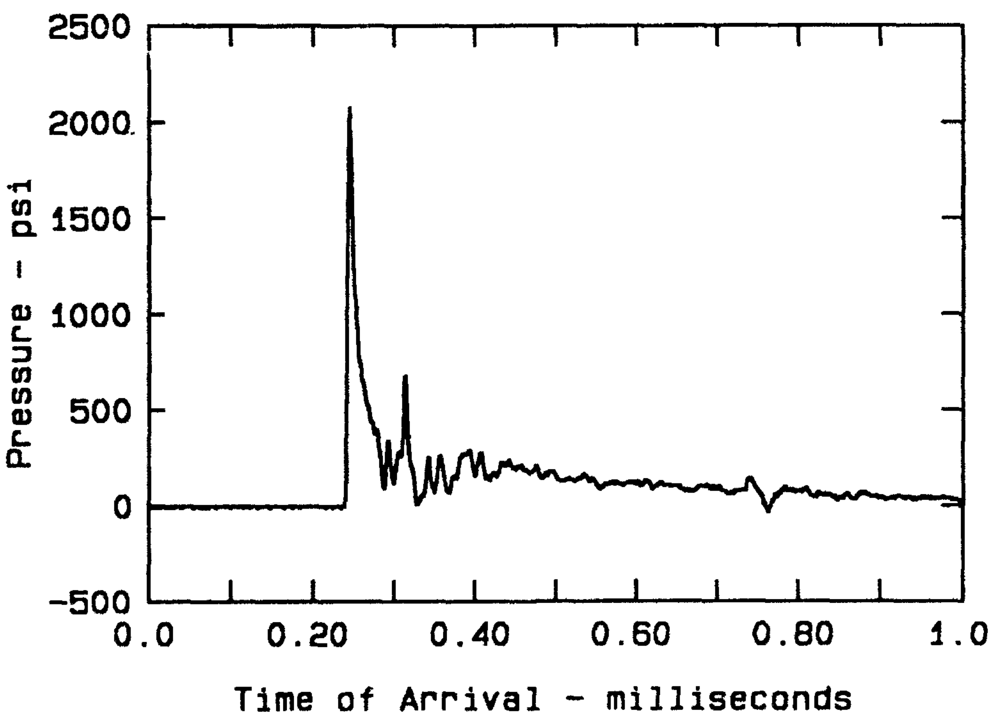


Figure 44. A longitudinal echo reflected from base of a 4-ft-thick slab having a TOA of 0.74 msec. The stress wave energy was created by an impact from a 0.87-g charge exploding underwater 0.5 ft above the concrete

10,000 psi, manufactured by PCB Piezotronics. Operation of the gage occurred in the broadband portion of the frequency response curve below resonance.

70. Numerous arrivals of waves can be seen from Figure 44, a typical TOA plot. The wave with the sharpest front and highest amplitude is the longitudinal direct wave arriving at 0.24 msec. The expected arrival time was calculated to be 0.256 msec based on the separation distance of 1.28 ft between the charge and the sensor and an approximate textbook velocity of 5,000 ft/sec for the longitudinal velocity in water.

71. Arriving just behind the direct wave is the lower-amplitude reflected longitudinal wave from the top surface of the concrete with a TOA of about 0.31 msec. The expected TOA was calculated to be 0.325 msec based on a calculated distance of 1.62 ft and the approximate textbook water velocity of 5,000 ft/sec. Finally, the low amplitude pulse with a TOA of 0.74 msec was the main pulse of interest. The TOA agrees with the time required for the pulse to travel from the explosive source to the concrete surface, refract into the concrete, reflect from the base of the concrete slab to the top surface of the concrete and to refract into the water to be received by the pressure gage (Krautkramer and Krautkramer 1977). Although rays of energy are emanating from the explosive source from many angles, there is only one particular angle and ray path that will satisfy Snell's law of refraction and reflection in the water and concrete and permit detection at the receiver. The angle of incidence from the water calculates to a value of 6.5 deg and the angle of refraction into the concrete is 8.3 deg.

72. Only the smaller charges, the 0.87-g and 22-g charges, produced unmistakable echoes from the base of the slab. The larger charges did not produce visible echoes. In both cases, the data record was untreated in terms of signal processing. The reason for the lack of echoes from the larger charges is not understood but may be a result of the difference between the shape of the wave front produced by the variable sizes of the charges in relation to the gage location distance. The small charges will approximate a better point source (and hence a better spherical wave front), since the ratio of the charge diameter to the travel path is smaller than for the larger diameter charges.

73. The ratio of the desirable pulse-echo signal amplitude to the undesirable direct wave and other noise must be improved if the technique is

to be used in the future for crack detection measurements in concrete. However, due to the fact that very little progress has been made by investigators in performing pulse-echo measurements in concrete by any means, it is an encouraging development that echoes were detected with this method. To the author's knowledge, there is no published report of any pulse-echo results from the testing of concrete by the use of explosives in water or air. It was not known *a priori* the longitudinal velocity of the field concrete or whether the concrete had been damaged by the previous blasts. This test verified the soundness of the concrete as the longitudinal velocity was calculated to be 13,470 ft/sec. Test cylinders measured at 28 days had shown that the average velocity was 14,000 ft/sec. However, one can never be sure that the samples taken are clearly representative of the final field-placed concrete. No more than a 5-percent difference in velocities for most situations is expected. The results are within that range of variation.

Accelerometer and Rebound Hammer on Basement Floor

74. Limited tests were made on determining the thickness of a concrete slab with an impact-resonant technique (Thornton and Alexander 1987). Previously, resonant-frequency measurements had been made in the time domain using continuous waves (Muenow 1963). However, these later impact tests involved analysis in the frequency domain. The received signal was displayed on a frequency analyzer. In this test the longitudinal resonance in the thickness direction was detected with a broadband pickup, i.e. a pickup that was broadband in the frequency range of the particular resonance of interest. Figure 45 shows a resonance at 4,200 Hz. The concrete slab tested was 1.5 ft thick and was backed by soil. The energy was introduced with a Schmidt rebound hammer, and the reverberations were detected with an accelerometer. The equation describing the relationship is

$$v = 2fl \tag{12}$$

where

v = concrete velocity, feet/second

f = frequency of resonance, hertz

l = thickness, feet

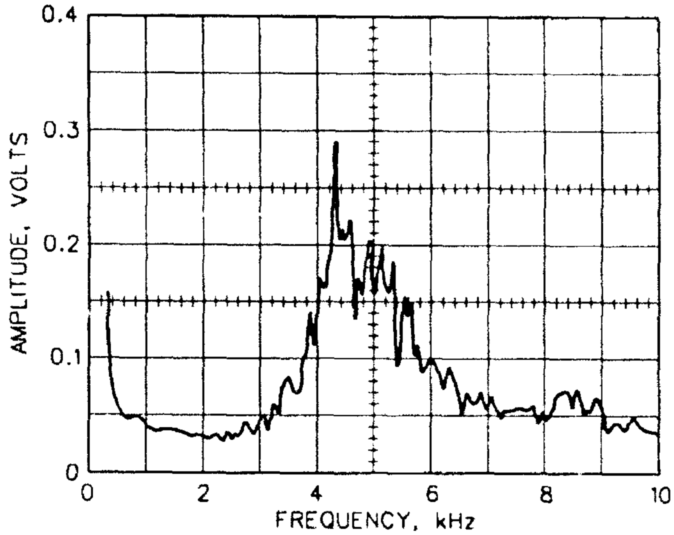


Figure 45. Response spectrum from a 1.5-ft-thick concrete slab from an impact with a rebound hammer. This represents an impact-resonance measurement rather than an impact-echo measurement

The above measurement gave a thickness of 1.55 ft. The ultrasonic velocity used in the calculation was determined on a concrete wall adjacent to the concrete slab which was measured with a through-transmission ultrasonic pulse-velocity instrument. The wall and floor were a monolithic placement at the time of construction.

75. Since the area of the hammer tip is small, the distribution of the energy introduced into the concrete would spread out in a hemispherical pattern with no apparent directivity. It would be considered a point source. When rays of energy enter at an interface at angles other than normal, mode conversion takes place and other waves are produced (such as shear waves and Rayleigh waves). See paragraph 7. These combine with the longitudinal wave to create unwanted resonances, which probably produced the broad band of energy displayed. However, the desired longitudinal resonance seems to dominate.

PART V: LABORATORY WORK ON RESONANT TRANSDUCERS

Considerations

76. At the beginning of this research program, the main emphasis was to damp a piezoelectric element so as to produce a frequency response curve that was uniform (flat) (Thornton and Alexander 1987). It was realized later that it was permissible for the transducer to ring for a few cycles (frequency response curve would have a peak) without obscuring the arrival of echoes. It is the excessive ringing in the transducers that is responsible for obscuring the arrival of echoes. Some ringing is in order, because it helps to sustain a large fraction of the high undamped sensitivity. If a transducer is being used as a receiver, it is necessary for the echo-excited ringing in the transducer to stop before a second echo from another interface arrives and can be recorded. The solution is to reduce the mechanical Q of the transducer without excessively sacrificing its sensitivity.

77. The idea of using a resonant ultrasonic receiver, rather than a nonresonant one, was then considered. The greatest sensitivity of a ceramic element exists at the resonant frequency. The ring-time need only be less than the time between echoes. Since an impact consists of broadband energy, it was considered that the higher-frequency components from an impact could be exploited to excite a damped, wideband receiver in the ultrasonic frequency range. The low-frequency, large-amplitude, compressional load-pulse components could be filtered out of the composite signal since it is noise for all practical purposes. Various undamped transducers were then tested. Almost every time, the resonance was so low in amplitude that it could not be seen in the presence of the lower-frequency components of the impact pulse. By using a high-pass filter with the cutoff frequency above the lower frequencies that make up the load pulse spectrum (but, below the resonant frequency of the crystal), the visibility of the resonance was enhanced.

Impact Measurements on Steel

78. Impacts can produce energy having frequencies in the megahertz range (Krautkramer and Krautkramer 1977). Figure 46 shows a test setup that

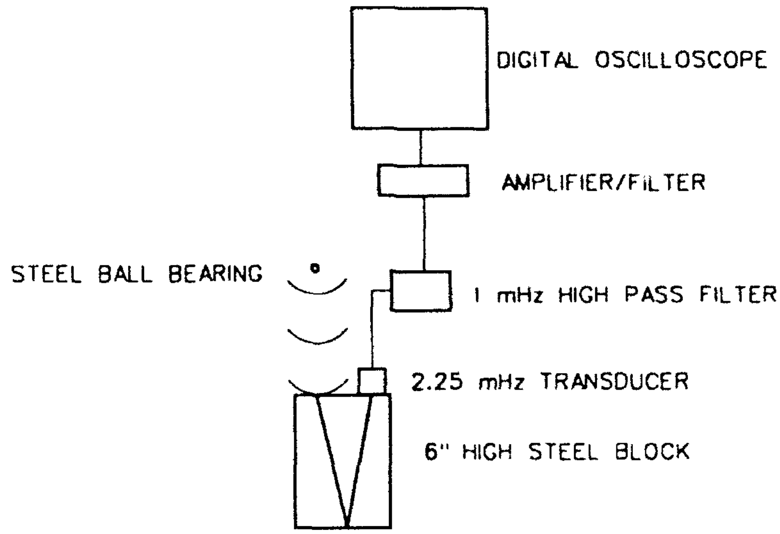


Figure 46. Measurement setup for making an ultrasonic pulse-echo measurement on a 6-in. high metal block with stress wave generation by impact from dropping a steel ball from a height of about 1 ft

verified this. A small 3/16-in.-diam steel ball was dropped from a height of 10 or 12 in. on a 6-in.-high steel block. (The smaller the diameter of the steel ball, the greater the production of higher-frequency energy). Steel was used to indicate the presence of high-frequency energy from an impact, since it is a better physical model than concrete. Even with the steel having a much smaller grain size with very low attenuation properties compared with concrete, the detection of the low level 2.25-MHz signal was pushing the limits of the capability of our electronics. The transducer has a Q of about 5 and was resonant at 2.25 MHz. It was 0.750 in. in diameter, a Gamma series Model D25907, manufactured by K. B. Aerotech, Inc.

79. An impact generates various modes of energy including longitudinal, transverse, and surface waves. Also, since the impact occurs over a small area, 1/2 in. in diameter (rebound hammer), it would be considered a point source for the frequencies below 100 kHz. Since the energy from a point source has a wide angle of divergence, various modes and unwanted waves are created. Because of the many modes of vibration and the various ultrasonic waves created especially at low frequencies, it is necessary to provide high-pass filtering to eliminate the lower-frequency waves.

80. The following data were obtained on a steel block that was 2.4 in. thick. The received signal shown in Figure 47 was first filtered with a dual-channel Krohn-Hite Model 3202R electronic filter. Cutoff was set at 1 MHz in the high-pass mode with both filter units in series to improve the attenuation below 1 MHz. The attenuation rate was 48 db/octave when both units were connected in series. The signal was then high-pass filtered again by a Panametrics Model 5055PR pulser/receiver. The high-pass cutoff was set at 300 kHz. The resulting signal was recorded on a Model 2090 Nicolet digital processing oscilloscope with floppy disc data storage. Usually each signal was recorded at 50 or 100 nanoseconds per point for a total of 1,024 points. Echoes can be seen occurring every 21 μsec. This TOA agrees with the measurement made from a commercial UPE unit for metals. Modes other than the desired longitudinal mode can be seen in the plotted curve, but the desired echo predominates. Also a 6-in. steel block was measured and the separation

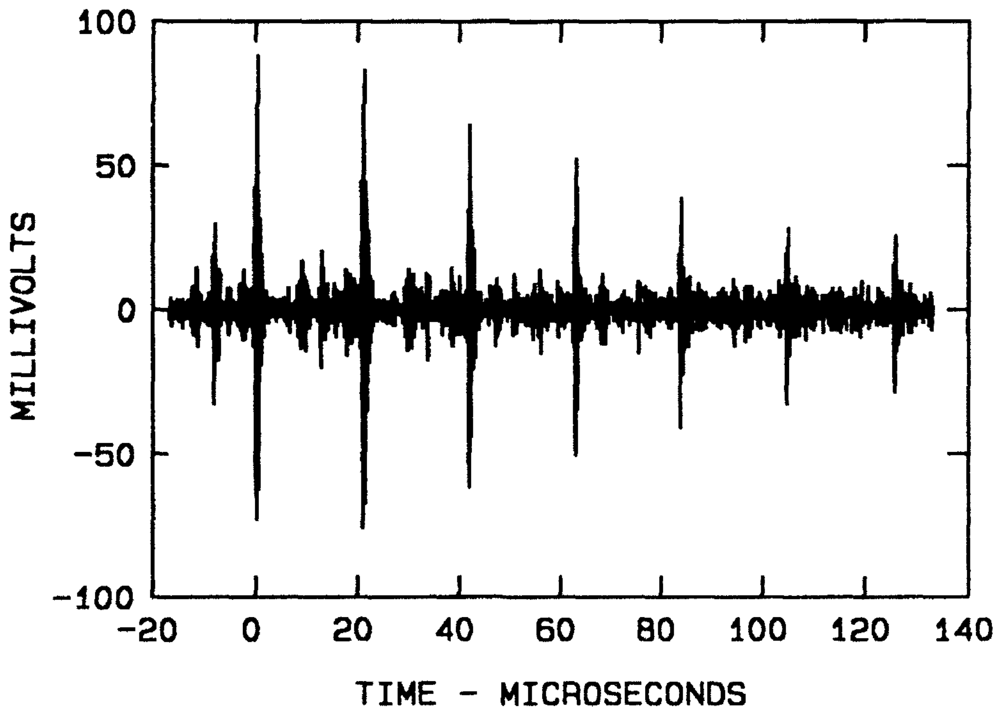


Figure 47. Echoes from a 2.4-in.-thick steel block with the stress wave energy introduced by impact from dropping a steel ball onto the surface. Center frequency of transducer is 2.5 MHz

time was 51 μsec for those echoes. The Panametrics Model 301S transducer, resonant at about 500 kHz, was also used successfully with both metal pieces.

81. Because of the large grain size, a transducer frequency of 2.25 MHz obviously produces a wavelength too short for typical concrete (less than 0.1 in.). However, the test demonstrated the potential of an impact from a steel ball to produce high-frequency ultrasonic energy. The measurements on steel help to define the type of signal processing that will be needed for similar lower-frequency impact measurements on concrete. The author is not aware of any literature that references UPE measurements on steel by impact.

High-Frequency Energy Transmitted through Concrete

82. A test was set up to determine if 200-kHz energy could be transmitted through 3 ft of concrete. The lead metaniobate (LM) transducer has its primary resonance at about 190 kHz (Figure 3). The rebound hammer was used to impact one end of the 3-ft concrete beam and the LM transducer was used as a receiver at the opposite end. The test setup is shown in Figure 48. The filter from the Panametrics Model 5055PR pulser/receiver was use to high-pass the energy above 100 Khz. A Wavetek Model 446B spectrum analyzer was used to measure the frequencies of the transmitted energy. Energy was transmitted that caused the LM transducer to resonate at 190 kHz (Figure 49).

Rebound Hammer and Lithium Sulfate Receiver

83. In Figure 50 a measurement setup is shown for making an UPE measurement on a 6-in.-thick concrete slab. The energy was introduced into the concrete with a rebound hammer and the echoes received by a damped lithium-sulfate receiver custom-built by Automation Sperry Company. The transducer was resonant at 100 kHz with a Q of 3. An electronic dual-unit filter Model 3202R by Krohn-Hite was used to bandpass energy centered around 100 kHz. Both units were connected in series. The lower cutoff frequency was set at 80 kHz, and the upper cutoff frequency was set at 150 kHz. The echoes can be seen in Figure 51. The echoes are equally spaced about 100 μsec apart, which is the correct two-way travel time for the longitudinal pulse. The velocity in this concrete is considered low at 10,000 ft/sec.

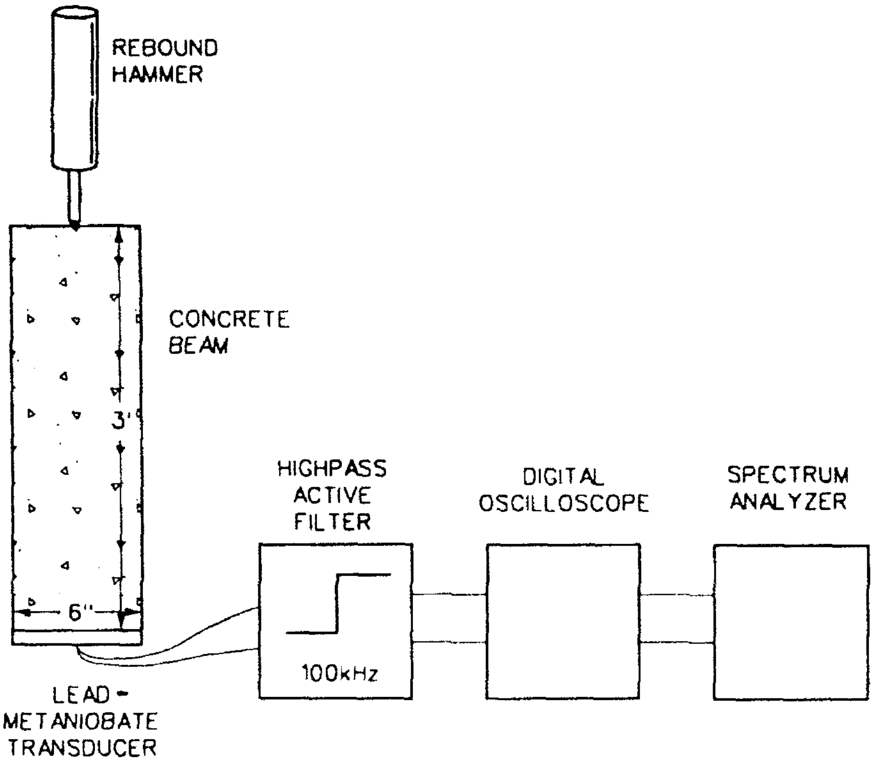


Figure 48. Measurement setup for detecting frequency of energy with lead-metaniobate transducer through 3 ft of concrete from impact with a rebound hammer

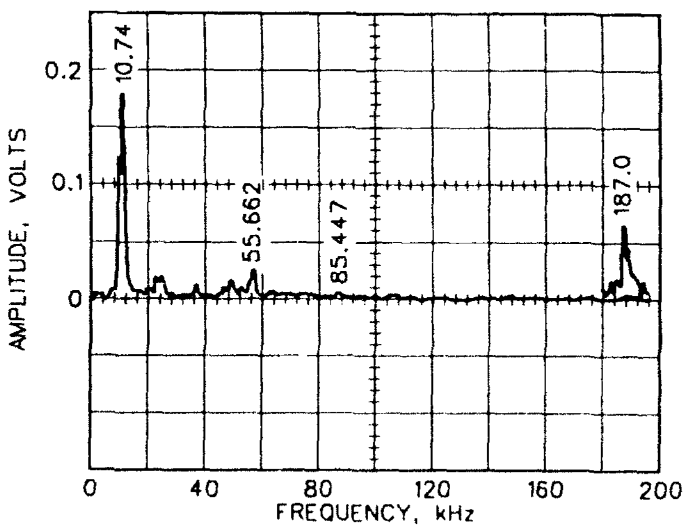


Figure 49. Spectrum of energy through 3-ft-long concrete beam. Concrete passed 190 kHz energy. Energy has been attenuated below 100 kHz by electrical filtering

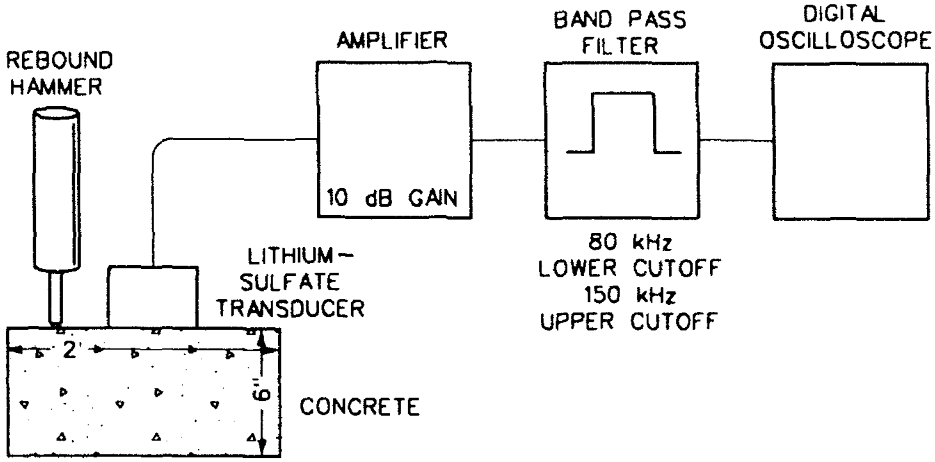


Figure 50. Measurement setup to make impact pulse-echo measurement on 6-in.-thick concrete slab using rebound hammer and lithium-sulfate transducer

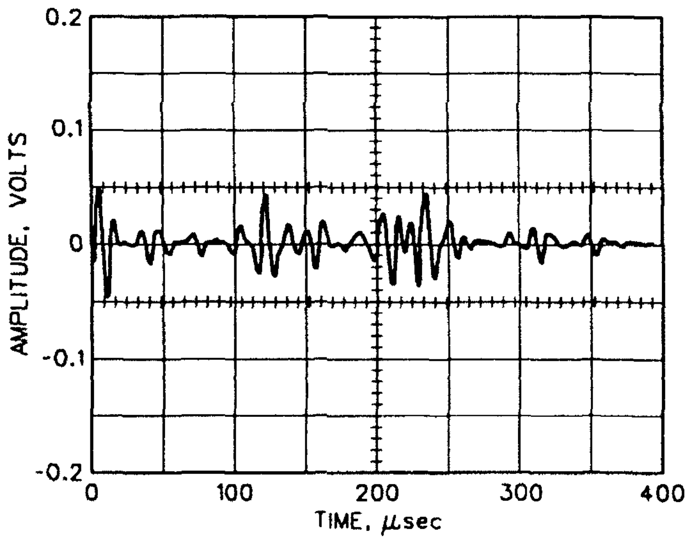


Figure 51. Ultrasonic pulse-echo measurement on 6-in.-thick concrete slab using a rebound hammer and lithium-sulfate transducer

PZT-C5500 Transducer and Rebound Hammer

84. A number of PZT-C5500 ceramic elements were purchased for the purpose of attempting to detect echoes in concrete from impact measurements. The elements were 1/4 in. in diameter and 1/4 in. in length. The undamped natural frequency was about 200 kHz. The bandwidth measurement is shown in Figure 52. A 2-in. backing of tungsten-loaded epoxy was used to damp the PZT element. The tungsten has a high acoustic impedance and closely matches that of the PZT. A 1/4-in.-long faceplate of aluminum was installed on the front face of the crystal. The transducer is shown in the lower left-hand corner of Figure 53. A small wire was soldered to the silver electrodes on the back side, and a thin foil of brass was cemented with silver epoxy between the aluminum face plate and front electrode of the crystal. The ground end was tied to this foil. The bandwidth measurements of the damped ceramic are shown in Figure 54. The main resonance has been reduced to 180 kHz and various extraneous modes of vibration are present due to the high mode-conversion properties of PZT.

85. Again, UPE measurements were made on the 9-in.-thick slab using the Model L-6 Schmidt hammer directly on the concrete (Figure 55). Disregarding the first pulse (beginning of oscilloscope trace does not coincide with beginning of impact), each succeeding pulse is roughly 100 μsec apart. (The velocity in this concrete is high at approximately 15,400 ft/sec) However, the response from a second impact would not always duplicate the previous one. Results were somewhat confusing but hopefully future investigation should reveal the source of confusion. It appears that surface waves are not that serious a problem even though, according to diffraction theory, there is no directivity in the beam profile created from a small-area impact.

86. Figure 56 shows the measurement setup used to make an UPE measurement on the 3-ft-long concrete beam. The rebound hammer was used to introduce the stress wave energy into the concrete, and the small diameter PZT-C5500 transducer was used to detect the echoes. A voltage divider was used to reduce the high impact-voltage so that it would not paralyze the input amplifier of the Panametrics Model 5055PR pulser-amplifier-filter. The high-pass filter was set to a cutoff frequency of 300 kHz, and the following Krohn-Hite Model 3202R active high-pass filter was set to a cutoff frequency of

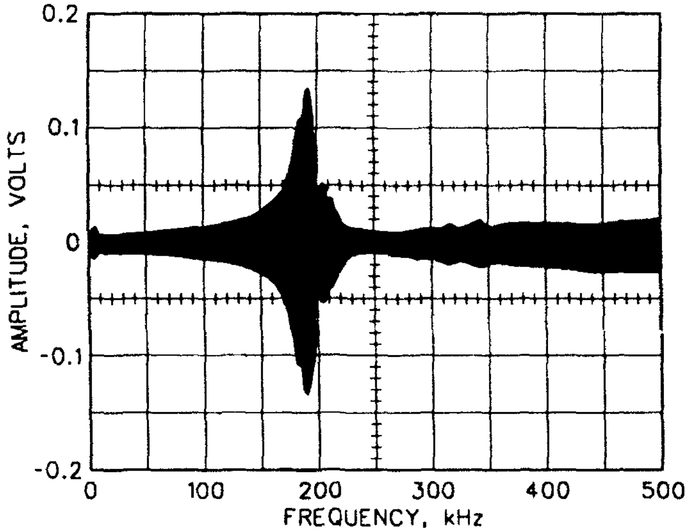


Figure 52. Bandwidth measurement of undamped PZT-C5500 element (1/4-in.-diam and 1/4-in. length)

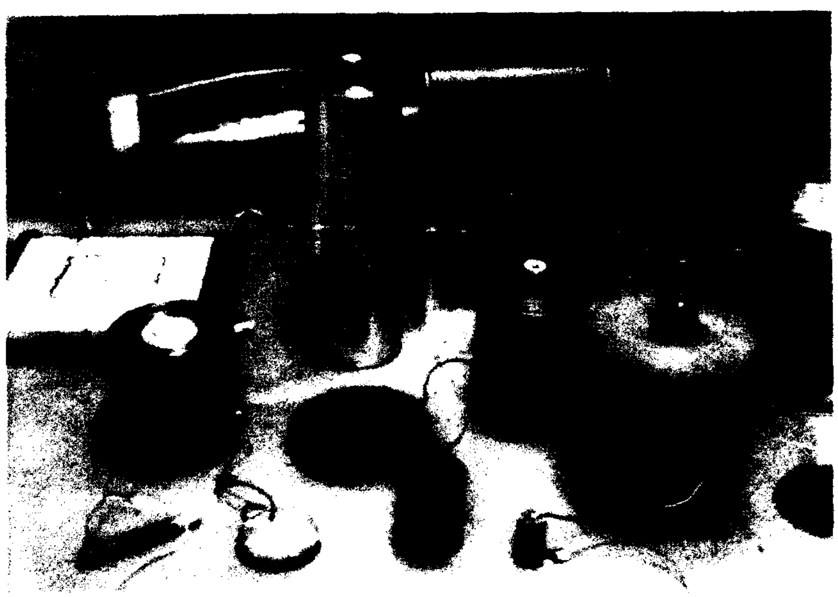


Figure 53. Various transducers constructed for ultrasonic pulse-echo measurements in concrete. Note PZT-C5500 transducer receiver in lower left-hand corner of photograph. The transducer has a 1/4-in.-long, 1/4-in.-diam aluminum faceplate and a 2-in. backing of tungsten-epoxy

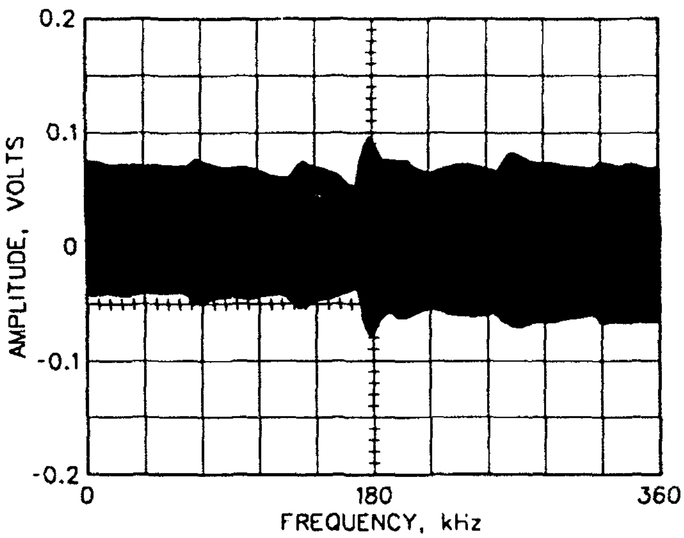


Figure 54. Bandwidth measurement of damped PZT-C5500 transducer

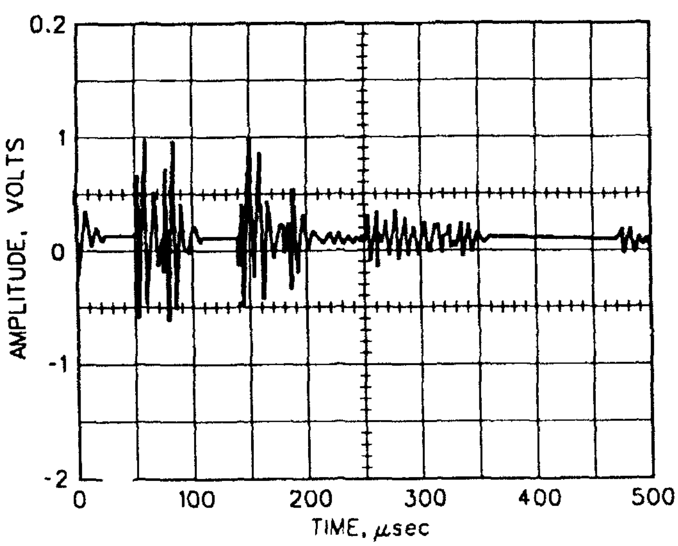
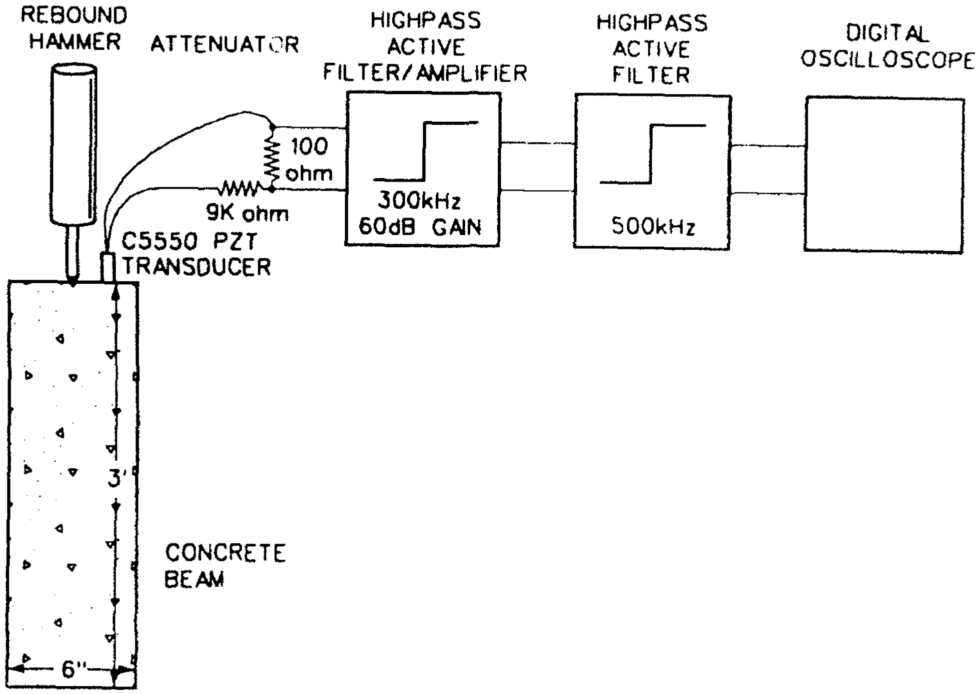


Figure 55. Pulse-echo measurements on 9-in.-thick slab using PZT-C5500 transducer receiver and Schmidt rebound hammer



Figure, 56. Measurement setup to make ultrasonic pulse-echo measurement on 3-ft-long concrete beam from impact with rebound hammer. Detection is with PZT-C5500 transducer. Frequencies below 500 kHz were highly attenuated by electrical filtering

500 kHz. The resulting signal was recorded on a Nicolet Model 2090 digital oscilloscope. The filtering attenuated the low-frequency sonic and ultrasonic energy considerably and permitted the higher frequency ultrasonic energy to dominate. As can be seen in Figure 57, echoes were received with separation times of approximately 500 μsec which, incidentally, is the correct two-way travel time in the 3-ft-long concrete beam for a longitudinal pulse. This funding is significant in that such high-frequency energy would not be expected to be transmitted through the highly attenuative concrete. The frequency of the pulses is centered around 750 kHz. Significant scattering, of course, occurred from the coarse aggregate as one would expect for that short a wavelength ($\approx$ 0.2 in).

87. Finally, in Figure 58 sonic echoes are shown resulting from an impact of the rebound hammer on one end of the 3-ft-long beam. The echoes were detected by the small PZT-C5500 transducer with operation occurring in the low-frequency broadband part of the frequency response curve without filtering. Every other echo is the correct echo time of 500 μsec. The impact pulse width from the rebound hammer is about 120 μsec.

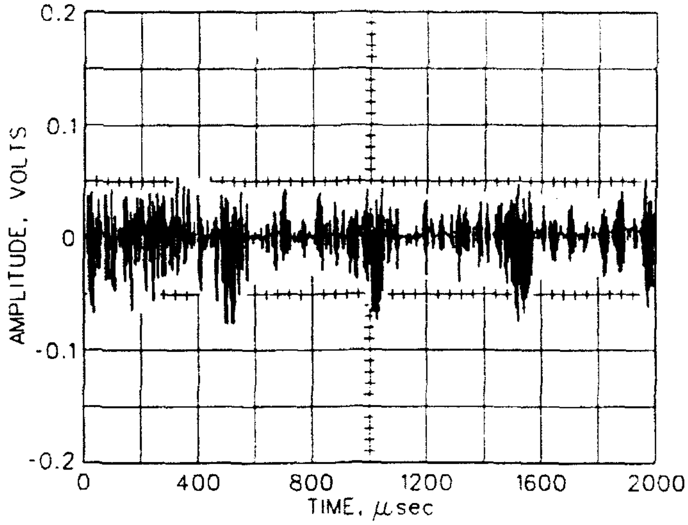


Figure 57. Ultrasonic pulse-echoes on 3-ft beam yields equally spaced echoes of approximately 500 μsec. Frequency of energy is 750 kHz

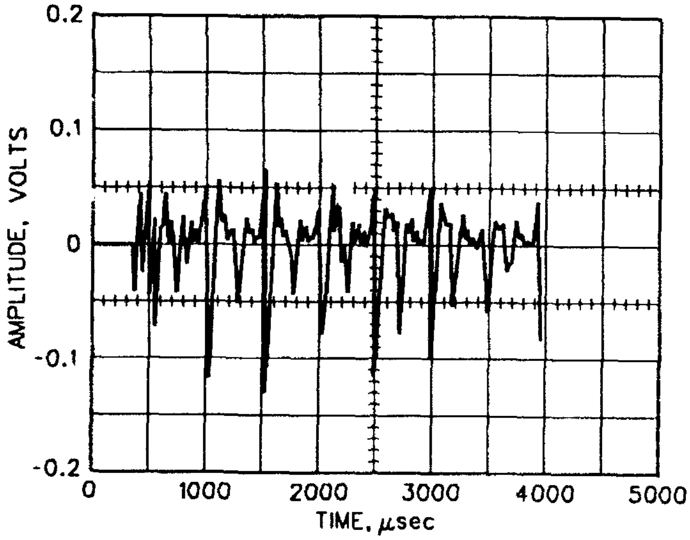


Figure 58. Ultrasonic pulse-echo measurement on 3-ft-long concrete beam by impact from a rebound hammer and using 1/4-in.-diam PTZ-C5500 transducer

PART VI: CONCLUSIONS

88. It is presently possible to make ultrasonic through-transmission measurements on hardened concrete. This can be accomplished through distances of about 25 ft using undamped transducers operating around 50 kHz with commercially available equipment. Intuitively one would suspect that UPE measurements could at least be made over a number of feet, even though the wideband transducers required for UPE measurements are not as sensitive as the narrowband transducers used in through-transmission measurements. So far, there does not exist in the literature any measurement data on the important property of concrete wave attenuation. This missing information makes it difficult to predict the potential penetrating power of an UPE system. The present use of impacts for crack-detection measurements is almost limited to listening by ear to the sounds emanating from sound and deteriorated concrete. (However, impact resonant-frequency measurements using a transducer receiver are common.) The results are highly subjective and are not useful above the range of hearing, the sonic range.

89. A number of sources of impact devices were tested in this investigation. Showing potential as appropriate sources of UPE energy for concrete structures are: steel balls shot from a compressed air gun, Schmidt rebound hammer, and small explosives. The pulse duration from a BB impact is around 10-20 μsec, which, fortunately, generates the highest energy in the range of frequencies optimum for concrete. The primary energy appears to be somewhat less than 100 kHz in frequency, although energy at harmonic frequencies would be higher. Also, the force level should be high enough to permit penetration depths of, possibly, tens of feet into concrete. When dropping large steel balls having diameters of 3/8 to 1/2 in., this is an excellent source of energy for performing resonant-frequency measurements mainly in the sonic range to just within the ultrasonic range. For smaller steel balls, 1/8 in. in diameter or less and shot from a compressed-air gun, this is a potential source of higher-frequency ultrasonic energy for making impact pulse-echo measurements in concrete.

90. The Schmidt hammer has a wide pulse-duration of about 70 μsec. This would appear at first thought to limit the generation of stress wave energy in the ultrasonic frequency range based on the large pulse width, but

that lack of energy is counteracted by the existence of high-frequency energy contained in the sharp rise time of the load pulse. Energy at a frequency of 190 kHz was easily detected through 3 ft of concrete demonstrating the penetrating ability of the rebound hammer. An UPE measurement was made on a 3-ft-long concrete beam with the transducer operating at a center frequency of 750 kHz. This indicated that high-frequency energy was contained in an impact pulse from a rebound hammer. Considerable scattering obviously occurred, since the wavelength (about 0.2 in.) was much shorter than the dimensions of the 3/4-in. coarse aggregate. Small explosive caps were capable of generating acoustic energy with the center frequency just above the sonic range. Although no practical impact UPE system was developed, numerous backwall echoes were measured from opposite surfaces of concrete structures.

91. It may be important to introduce some damping into a transducer to bring the bandwidth into the appropriate range of frequencies without excessively attenuating the sensitivity. The measurement of the bandwidth should be performed carefully, as outlined in the body of the report, to test the performance of the transducer and the success of the damping operation. Tungsten powder mixed with epoxy will create a backing that closely matches the high acoustic impedance of piezoelectric materials. Electrical bandwidth measurements do not tell the complete story. The frequency spectrum of echoes from tests on actual specimens should be measured also, since the mechanical bandwidth may differ from the electrical bandwidth. A transducer's receiving sensitivity can be improved considerably by tuning out the undesirable static capacitance by the introduction of an external inductor in the transducer circuit.

92. With only a limited investigation, it would seem that two of the main concerns of impact measurements are not as serious a problem as the theory would indicate: (1) that an ultrasonic source of small area will create surface waves that will interfere with detection; and (2) that a sharp impact will not produce energy with high enough frequencies to introduce ultrasonic energy into the concrete, near 200 kHz. One disadvantage of impacts is that the spherical wave front from an impact tends to generate wave types other than the desired longitudinal wave by mode conversion. Also another disadvantage is the difficulty in locating the source of the reflecting feature in the concrete since a wide-angle cone-shaped sound

pattern will transmit (and reflect) energy over a large volume underneath the hammer. If the source produced a small-angle cone-shaped pattern, all reflecting features could be easily located; they would be directly under the hammer. An impact hammer with a short contact time will generate ultrasonic energy (> 20,000 Hz) as well as even higher amplitude sonic energy (< 20,000 Hz).

93. The response from a piezoelectric receiving element due to an impact made on a concrete plate might have a dynamic range as high as 80 db (100,000 times) or greater separating the amplitude level of the sonic frequencies from the ultrasonic frequencies. Most electronic amplifiers, oscilloscopes, and filters will not respond over such a large range. It is then necessary to perform high-pass filtering to recover the low-level amplitude high-frequency components from the high-level amplitude low-frequency components. It is not recommended that resistive networks be used to attenuate the signal because all frequencies will be affected equally. Active filters cannot be used in the front-end stage because the operational amplifier would be paralyzed by the high-voltage output from the transducer. Passive filters which consist of passive components such as resistors, capacitors, and inductors do not saturate and breakdown due to high signal levels and, therefore, should be used. Because of the large dynamic range, it will be necessary to have at least a rolloff attenuation of about 24 db/octave and a larger rolloff may be necessary. A one-pole filter yields only a rolloff of 6 db/octave.

94. Specific details are given in this report on model numbers and manufacturers of equipment so that interested parties can easily continue this research. It is believed that significant gains will be made in this research when some sophisticated DSP techniques are applied to the problem. The surface has only been scratched in applying DSP to this problem and that appears to be the key for bringing out the desired hidden information.

PART VII: RECOMMENDATIONS

95. The investigation showed promise that an impact-echo system could be developed to operate in the ultrasonic frequency range. It is recommended that the research be continued under the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) II Research Program to develop an impact UPE system that will hopefully penetrate tens of feet into large Corps of Engineers structures such as locks and dams. The following steps are recommended as one approach to UPE development by impact.

a. A large concrete structure (physical model having a thickness of tens of feet with large lateral dimensions to reduce reflections from the sides of the structure) should be found or built to use for testing. The first model should contain no steel or foreign objects to interfere with the signals.

b. A variety of impact hammers should be tested having short pulse durations with high-force levels. The rebound hammer should be modified to obtain a variety of signal characteristics from the load-pulse. A BB gun should be tested for firing high-velocity steel projectiles.

c. Various undamped transducers should be tested at the different harmonics of the fundamental and slightly damped with tungsten/epoxy, if necessary. Bandwidth curves should be measured to determine the effect of the damping.

d. The total signal should be captured, if possible, without prefiltering until the signals can be treated using a suitable signal processing software package. A waveform recorder should be used that can store as many bits as possible but not less than 16 bits due to the large dynamic range of signals and noise. It may be necessary to find signals that are 80 to 100 db below the level of the noise.

e. An automatic processing system should be developed that can search for weak but definite echoes in the complicated signals. The system should be capable of automatically adjusting to set the correct center frequency, bandwidth, and amplification for display.

f. The automatic filter system should be installed into a real-time DSP chip that will permit instant results in the field.

REFERENCES

American Society for Testing and Materials. 1992. "Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding (D 4580)," 1987 Annual Book of ASTM Standards, Vol 04.03, Philadelphia, PA.

__________. 1992. "Standard Test Method for Rebound Number of Hardened Concrete (C 805)," 1992 Annual Book of ASTM Standards, Vol 04.02, Philadelphia, PA.

Alexander, A. Michel. 1980 (Apr). "Development of Procedures for Nondestructive Testing of Concrete Structures; Report 2, Feasibility of Sonic Pulse-Echo Technique," Miscellaneous Paper C-77-11, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

__________. 1981 (Nov). "Development of Procedures for Nondestructive Testing of Concrete Structures; Report 3, Feasibility of Impact Technique for Making Resonant Frequency Measurements," Miscellaneous Paper C-77-11, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

__________. 1991 (Oct). "Resonant-Frequency and Pulse-Echo Measurements," International Advances in Nondestructive Testing, Volume 16, Gordon and Breach Publishers, Inc., Philadelphia, PA, pp 193-215.

Bradfield, G. 1948 (Mar). "New Electro-Acoustic Transducer Operating with Short Pulses," Electronic Engineering, Vol 20, No. 241, pp 74-78.

Cady, Walter Guyton. 1964. "Piezoelectricity," Dover Publications, Inc., New York, Vol I, p 335.

Canfield, Joe R., and Moore, Willard H. 1967 (Jun). "Development of Instrument for Nondestructive Measurement of Concrete Pavement Thickness," Research Project No. 1-9-63-61 Report No. 61-1F, Materials and Test Division, Texas Highway Department in cooperation with US Department of Transportation, Federal Highway Administration, and Bureau of Public Roads, Austin, TX.

Carlin, Benson. 1960. Ultrasonics, 2nd ed., McGraw-Hill, New York.

DeFrance, J. J. 1963. General Electronics Circuits, Holt, Rinehart and Winston, New York, p 448.

Desai, P. J., Marwadi, S. C., Wedpathak, A. V., Guha, S. K., and Nand, Krishna. 1974. "A Sonic Method for the Detection of Deep Cracks in large Structures," Indian Concrete Journal, Vol 48.

Edo Western Corporation Brochure. "Piezoelectric Ceramics," EWC 02025-8302, Western Division, Salt Lake City, Utah, 36 pp.

Gulton Industries, Inc. 1980. "Design Notes on Piezoceramics," ICN8011, Piezo Products Division, Fullerton, CA.

Hewlett-Packard Co. 1981 (Nov). "The Fundamentals of Signal Analysis," Application Note 243, Palo Alto, CA, 57 pp.

Howkins, S. D. 1968. "Measurement of Pavement Thickness by Rapid and Non-destructive Methods," NCHRP - National Cooperative Highway Research Program Report 52, Washington, DC.

Hueter, T. F., and Bolt, R. H. 1955. Sonics: Techniques for the Use of Sound and Ultrasound in Engineering and Science, Wiley, New York.

Jones, R. 1953 (Jan). "Testing of Concrete by Ultrasonic-Pulse Technique," Proceedings of the 32nd Annual Meeting, Highway Research Board, Washington, DC, p 260.

__________. 1962. Non-destructive Testing of Concrete, Road Research Laboratory, Cambridge University Press, Cambridge, Great Britain, p 47.

Kossoff, G. 1966 (Mar). "The Effects of Backings and Matching on the Performance of Piezoelectric Ceramic Transducers," IEEE Transactions on Sonics and Ultrasonics, Vol su-13, No. 1, pp 20-30.

Krautkramer, J., and Krautkramer, H. 1977. Ultrasonic Testing of Materials, 2nd ed., Springer-Verlag, New York.

Lutsch, A. 1961 (Sep). "Solid Mixtures with Specified Impedances and High Attenuation for Ultrasonic Waves," Journal of Acoustical Society, Vol 34, pp 131-132.

Malhotra, V. M. 1976. "Testing Hardened Concrete: Nondestructive Methods," ACI Monograph No. 9, American Concrete Institute, Detroit, MI.

Muenow, Richard. 1963 (Sep). "A Sonic Method to Determine Pavement Thickness," Journal of the Portland Cement Association Research, Vol 5, No. 3, pp 8-21.

__________. 1990 (Oct). "Concrete Nondestructive Testing-Equipment and Application," Proceedings Nondestructive Evaluation of Civil Structures and Materials, University of Colorado, Boulder, CO.

Pender, Harold, and McIlwain, Knox. 1950. Electrical Engineers Handbook, 4th ed., pp 5-27, Wiley, New York.

Redpath, Bruce B. 1973 (May). "Seismic Refraction Exploration for Engineering Site Investigations," Technical Report E-73-4, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sansalone, Mary, and Carino, Nicholas J. 1986 (Sep). "Impact-echo: A Method for Flaw Detection in Concrete Using Transient Stress Waves," NBSIR 86-3452, National Bureau of Standards, Gaithersburg, MD.

Stein, Peter K. 1964. Measurement Engineering; Vol 1, Basic Principles, Stein Engineering Services, Inc., Phoenix, AZ.

Thornton, H. T., and Alexander, A. M. 1987 (Dec). "Repair, Evaluation, Maintenance, and Rehabilitation Research Program, Development of Non-destructive Testing Systems for In Situ Evaluation of Concrete Structures," Technical Report REMR-CS-10, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Vernitron Piezoelectric Division. 1979 (Feb). "Modern Piezoelectric Ceramics," Bulletin PD-9247 and 9247-2, Bedford, OH.

Walker, D. C. B., and Lumb, R. F. 1964 (Jul). "Piezoelectric Probes for Immersion Ultrasonic Testing," Applied Materials Research, pp 176-183.

Washington, A. B. G. 1961. "The Design of Piezoelectric Ultrasonic Probes," British Journal of Nondestructive Testing, Vol 3, pp 56-63.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1993

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Impacts as a Source of Acoustic Pulse-Echo Energy for Nondestructive Testing of Concrete Structures

5. FUNDING NUMBERS
Civil Works Research Work Unit 32638

6. AUTHOR(S)
A. Michel Alexander

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAE Waterways Experiment Station
Structures Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report REMR-CS-40

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The construction industry lags behind the aerospace, automotive, and other industries in the development of nondestructive testing systems for assessing the condition of one of their primary building materials, concrete. A research investigation was made to determine the feasibility of using impacts to create high-energy, high-resolution stress waves for making sonic and ultrasonic pulse-echo (UPE) measurements in concrete. No method presently exists to probe the deep interior of large concrete structures such as locks and dams. Impacts from air guns that shoot steel balls, the Schmidt rebound hammer, and small explosives demonstrate the potential for generating the appropriate kind of energy for UPE measurements. Measurements were made to demonstrate that the frequencies generated by these types of impacts are in the proper range for making UPE measurements in concrete, i.e. less than 200 kHz. Also, it was demonstrated that the energy level from these impact sources was high, suitable for penetrating large distances. Various criteria are discussed in this study that have a bearing on the development of a practical impact UPE system for concrete structures.

14. SUBJECT TERMS

Concrete	Nondestructive testing	Sonics
Construction	Pulse-echo	Ultrasonics
Impact-echo	Resonant frequency	

15. NUMBER OF PAGES
84

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT